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DYNAMICS, TRANSPORT AND CHEMICAL KINETICS OF COMPARTMENT FIRE EXHAUST GASES

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1.0 SUMMARY

The total number of civilian deaths in home fires throughout the United States in 1994 dropped to an all time low of 3,425 people (Karter, 1995). Though this news is encouraging, the statistics for the cause of deaths in building fires reveals some less encouraging news regarding smoke inhalation deaths.

The cause of death in building fires continues to be dominated by smoke inhalation. Smoke inhalation was responsible for 76% of the deaths in building fires in 1990 (Hall and Hardwood, 1995). From 1980 to 1990, the percentage of smoke inhalation deaths in structure fires has risen 1% each year. If these numbers are extrapolated to 1994, smoke inhalation was responsible for 80% of the deaths in structure fires in 1994. Since the level of carboxyhemoglobin in a victim's blood stream (>50%) was the measure of whether or not death was caused by smoke inhalation, the smoke inhalation data conveys that an increasing percentage of deaths in building fires are the result of carbon monoxide poisoning.

Two-thirds of the smoke inhalation victims are found at locations distant from the room of fire origin (Gann et al., 1994). This situation is demonstrated vividly in two unfortunate cases during the last decade, both in nursing homes. On October 5, 1991 at the Hillhaven Nursing Home in Norfolk,Virginia, a fire in a patient's room resulted in the death of 13 people (Nelson and Tu, 1991). Each victim died of carbon monoxide poisoning and was located in a room or position down the hallway from the room containing the fire, see Fig. 1. Eleven of the victims were in rooms on the opposite side of the hallway from the burning room. This was attributed to a wind from the south causing a draft which drove the toxic gases across the hallway into the victims' rooms. The results discussed in this paper offer another possible explanation why the majority of people who perished were on the opposite side of the hallway from the room containing the fire. A similar type fire in a Southern Michigan hospice claimed the lives of 8 people, 6 of which were at locations down the hallway from the room containing the fire (Nelson, 1988).

Research at the Building Fire Research Laboratory at VPI&SU over the past seven months have concentrated on determining conditions where high concentrations of carbon monoxide (CO) can be transported to locations remote from the fire origin. Experiments were done with the compartment containing the fire placed on the side of the dead end of the hallway, see Fig. 2. The other end of the hallway (opposite the dead end) was blocked except for a small opening allowing the escape of combustion gases from the hallway. This limited the air entrainment into the hallway, in addition to forcing some of the combustion gases in the hallway to recirculate back toward the compartment.

The relation of the CO yield leaving the hallway, determined through sampling in the exhaust duct, with the compartment global equivalence ratio, GER, was examined. The results showed that the CO yield had a very weak dependence on the geometric conditions at the hallway entrance while a 25% reduction in the CO yield was observed upon the occurrence of external burning from the compartment. CO was seen to be transported out of the hallway, 4.41 m down the hallway from the window where the compartment fire gases enter the hallway, in concentrations as high as 1.6%-wet with external burning and 1.9%-wet in fires when no external burning occurred in the hallway. The gas concentrations within the hallway upper-layer were highly non-uniform for this compartment-hallway geometry. In particular, high levels of CO (1.6-2.4%-wet) were present on the side of the hallway opposite the compartment while lower levels of CO (0.4-1.0%-wet) were seen on the side of the hallway where the compartment was located.

The following pages contain a brief discussion of the facility and the experimental procedure used to generate the new data. This will be followed by an in-depth presentation of the experimental results using the compartment-hallway configuration seen in Fig. 2 with an elevated doorway and a window connecting the compartment to the hallway. The effects of the geometry where the gases enter the hallway and the stoichiometry of the gases entering the hallway on the oxidation of CO will be explained through experiments where sampling was performed downstream of the hallway and in-hallway (and in-compartment). The effects of a large soffit at the exit of the hallway, which allows ambient air to entrain into the hallway, will be mentioned. This will be followed by a summary of the conditions which affect the oxidation of CO in both a positive and negative manner. Finally, the report includes some highlights of work which will be performed in the near future.

2.0 EXPERIMENTAL

2.1 Facilities and Methods

The study performed during the reporting period was with a compartment-hallway orientation more common in buildings. For these experiments, the compartment has been moved to the side of the hallway at the closed end, forming a L-shape structure, see Fig. 2. The hallway is 1.22 m wide and 5.18 m long. The hallway height depends on the soffit height where the gases enter the hallway (hallway entrance). The hallway height is 1.47 m high with no soffit and 1.67 m high with a 0.20 m soffit.

The air entrainment into the hallway is limited by blocking most of the (open) end of the hallway where the fume hood is located. A 1.22 m wide, 0.20 m high opening at the end of the hallway allowed combustion gases to escape the hallway into the fume hood. These experiments, to a first order approximation, model a dead end corridor with the gases exiting the hallway representing those gases which escape the hallway to other rooms or hallways.

Liquid hexane pool fires are burned in the center of the compartment with the mass of the fuel constantly being monitored using a load cell. Experiments were performed where oxygen was entrained into the compartment from the hallway (air inlet duct blocked off), and where oxygen was entrained into the compartment from the ambient atmosphere through the inlet duct connected to the compartment.

When oxygen was entrained into the compartment from the hallway, a door 0.50 m wide and 0.75 m high (0.375 m^2) connected the compartment to the hallway, see Fig 3. During a fire, combustion gases escaped the compartment through the top of the door while gases from the hallway entered the compartment through the bottom of the door. The bottom of the door is 0.72 m above the floor of the hallway and is at the level of the top of the fuel pan inside the compartment.

When oxygen was entrained into the compartment from the ambient atmosphere, air entered the compartment through the air distribution plenum which is connected to the atmosphere by the air inlet duct 0.30 m in diameter, see Fig. 2. The mass flow rate of air into the compartment is controlled by placing different size orifices on the end of the circular duct connected to the plenum. The combustion gases exited the compartment through a widow was varied in size.

Gas concentrations and temperature variations were measured downstream of the hallway in the exhaust duct and in a variety of locations within the facility. Two Rosemont Analytical NDIR model 880 analyzers were used to measure the dry concentrations of CO and CO_2. An Oxymat 5E paramagnetic analyzer was used to measure O_2 dry concentrations. The UHC were measured as ethylene using a Gow Mac FID. By assuming a stoichiometric ratio of H_2O and CO_2, the dry concentrations of CO, CO_2 and O_2 were converted to wet concentrations. All gas concentrations contained within this report are reported on a wet basis. Temperature profiles were measured in both the front corner of the compartment and at various locations within the hallway upper-layer using aspirated Type K thermocouples.

2.2 Parameters and Tests

Many parameters (fluid mechanical, chemical and thermal) are expected to affect the transport of CO. From the previous study performed Ewens (1994), the geometric conditions at the hallway entrance were seen to have a significant effect on the oxidation of CO and unburned hydrocarbons (UHC). In both the Hillhaven fire and the Southern Michigan hospice fire, there was a limited amount of oxygen in the hallway where high concentrations of CO were transported to patients' rooms remote from the burning room. To simulate this environment, the Building Fire Facility at Virginia Tech was altered so the air entrainment into both the compartment and the hallway were limited. The parameters investigated to date are:

- door (0.375 m^2) versus window opening
- window size (0.12, 0.08 and 0.04 m^2),
- fire size, altered by various fuel pan diameters (0.28, 0.23, 0.20, and 0.15 m),
- air entrainment rate into the compartment, via different air inlet duct orifice diameters (none (0.30), 0.25, 0.20, 0.15 m) {when applicable},
- oxygen entrainment into the compartment (oxygen containing combustion gases or ambient air),

- air entrainment into the hallway (fully open or closed except a 1.22 m wide, 0.20 m high opening), and
- hallway entrance soffit height (0 and 0.20 m high).

In experiments containing the door opening, species sampling and temperature measurements were performed in the front and the back of the compartment upper-layer, along the height of the doorway, along the length and height of the hallway, at the hallway exit and downstream of the hallway in the exhaust duct. One experiment was performed to investigate the effect of a larger fuel pan.

In the Southern Michigan hospice fire and the Hillhaven fire, ambient air was entrained into the compartment through a broken out window. Using the experimental facility shown in Fig. 2, experiments were performed to investigate the effect of limited ambient air entrainment into the compartment on the CO levels. Gases were initially sampled downstream of the hallway in the exhaust duct (termed downstream sampling) to attempt to correlate the yield,

$$X_{yld} = \frac{\dot{m}_X}{\dot{m}_{fuel}} \tag{1}$$

of the combustion gases, mainly CO and UHC, with the global equivalence ratio (GER),

$$\phi = \frac{\left(\dot{m}_{fuel} \middle/ \dot{m}_{air} \right)}{\left(\dot{m}_{fuel} \middle/ \dot{m}_{air} \right)_{st}} \quad (2),$$

(defined as the fuel vaporization rate divided by the air entrainment rate into the compartment all normalized by the stoichiometric fuel to air ratio during steady-state burning inside the compartment). A temporal correction, equal to the convection time for the gases to travel from the compartment to a downstream location, was applied to all gas samples downstream of the compartment. This was done so that the mass flow of gas could be related to the fuel vaporization rate which gave rise to these conditions. The experiments in which samples were taken in the exhaust duct included the following cases:

- entrance soffit heights of 0 and 0.20 m,
- orifices diameters of 0.30 (no orifice), 0.25, 0.20, and 0.15 m,

- fuel pan diameters of 0.28, 0.23, 0.20, 0.15, and 0.10 m, and
- window sizes of 0.12, 0.08 and 0.04 m^2.

The second type of experiments involved gas sampling and temperature measurements in the front and the back of the compartment, and at various locations in the hallway, to study the evolution of the gases as they were transported down the hallway. With no soffit at the hallway entrance, the hallway experiments were performed with a 0.20 m diameter fuel pan using all three window sizes reported above. With a 0.20 m soffit at the hallway entrance, experiments were performed with a 0.20 m diameter fuel pan and a 0.04 m^2 window. The global equivalence ratio inside the compartment for these experiments was kept at approximately ϕ=3 through varying the air entrainment into the compartment by attaching the appropriate orifice diameter to the air inlet duct. So the data from experiments with different conditions could easily be compared, the species concentrations and temperatures were normalized to the following values unless otherwise noted: CO with 4%, UHC with 8%, CO_2 with 20%, O_2 with 21% and temperature with 1300K.

3.0 RESULTS OF DOOR EXPERIMENTS

The first scenario investigated was a compartment connected to a hallway by a door opening where both combustion gases exited and oxygen entered the compartment, see Fig. 3. Just prior to flashover, the hallway is filled with a deep, dark layer of combustion gases. Some of these combustion gases manage to exit the hallway and enter the fume hood while the balance recirculates back toward the compartment. During the post-flashover period of the compartment fire, no persistent external burning occurred in the hallway. Instead, short periods of external burning were observed which, at times, had the appearance of a flame floating "aimlessly" in the upper-layer of the hallway.

The ideal fire size, defined as

$$Q = \dot{m}_{fuel} \Delta H_c \qquad \text{[kW]} \qquad (3)$$

where $\dot{m}_{fuel}$ is the fuel vaporization rate and ΔH_c is the heat of combustion of hexane (44,735 kJ/kg), for the fires in the reported experiments averaged 250 kW ± 12kW.

From the temporal plot of the compartment temperature 0.05 m below the ceiling shown in Fig. 4, the upper-layer temperature inside the compartment is constant during the majority of the post flashover period. The compartment temperatures for this scenario were approximately 100 K lower than compartment temperatures seen in experiments performed by Ewens (1994). It should also be noted that these compartment temperatures are not much higher than the temperature at which the CO oxidation reaction begins to slow down significantly; 950 K (Yetter et al., 1991) . Through visual observation, the compartment appears to be completely engulfed with hot gases as opposed to a two-layer environment where there is a distinct separation between the air and the upper-layer hot gases. The CO level in the upper-layer of the compartment was seen to be nearly the same in the front and the rear reaching a peak value of approximately 4.0%.

At the door, hot combustion gases are exiting the compartment while cooler oxygen containing gases are entering the compartment. The variation in the species concentrations and the temperatures along the height of the door is shown in Fig. 5. (The reader should note that the data points are connected using splines and unrealistic curvatures should be ignored.) By estimating the inflection point of the temperature profile, the interface between the inflow and outflow of gases was approximately 1.04 to 1.08 m above the floor (0.43 to 0.39 m below the ceiling). The gases exiting the compartment 0.05 m below the top of the door have CO levels of nearly 3.0% with no oxygen while the gases entering the compartment through the lower portion of the door contain at least 0.12% CO and no more than 18% O_2.

Shown in Fig. 6 are the species concentrations and gas temperatures 0.05 m below the ceiling at different locations along the hallway. The origin of abscissa corresponds to the middle of the door. The first two points are from experiments where gases were sampled across the hallway. The slight rise in the CO_2 concentration during the first 0.35 m of the hallway, see Fig. 6, demonstrates a small amount of CO being oxidized while the gases are being transported across the hallway. After the gases have turned and begin to travel down the hallway, the decrease in CO and UHC at the 0.85 m position is due to dilution of the gases with the cooler entrained combustion gases below since the CO_2 levels are also decreasing. After traveling to the 1.32 m position, upper-layer gas concentrations in the center of the hallway are relatively unchanged for the remaining length of the hallway. The temperatures in the hallway were never higher than approximately 850K which is on the lower end for CO oxidation. It will be shown in chapter **4.** that the gases along the middle of the hallway are in a non-reacting region, and that the reacting region in the hallway for this compartment-hallway orientation is along the wall across the hallway from the compartment. Since the gases in the middle of the hallway are virtually non-reactive, decreases in the concentration of CO, UHC and CO_2 are mostly a result of dilution, as demonstrated through these results.

High levels of UHC, 1.6%, are present at a location quite distant from the burning compartment. Near the end of the hallway, the concentration of CO is still at a lethal level of 1.7% in the presence of 8.8% O_2. The exposure time

$$t = \left(\frac{197(COHb)}{CO^{0.858}} \right)^{1.587} \quad \text{[min]} \qquad (4)$$

where;

t = exposure time, [minutes]
COHb = carboxyhemaglobin level in the blood, [%]
CO = level of carbon monoxide exposure, [ppm]

necessary for a particular concentration of CO (in ppm) to cause a fatally high concentration of carboxyhemaglobin (COHb) in the bloodstream can be estimated by assuming a 50% COHb level causes death (Peterson and Stewart, 1970). From Eqn. (4), a person needs to be exposed to the levels of CO seen leaving the hallway for less than 4 minutes before lethal levels of COHb are present in the bloodstream.

During the compartment fire post-flashover period, flashes of external burning were seen to occur in the hallway. From the temporal plot of the species concentrations at the 1.32 m position in the hallway, shown in Fig. 7, these flashes of external burning can be seen by a decrease in CO, UHC and O_2 with a corresponding increase in the CO_2. Also shown in Fig. 7, is a typical fuel vaporization rate curve. The compartment temperatures from this experiment are shown in Fig. 4.

The concentrations of species along the height of the hallway, 1.32 m down the hallway from the middle of the door, are shown in Fig. 8. The boundary between the upper-layer gases and the lower-layer gases can be seen in the species concentration profiles to be 1.20-1.16 m above the hallway floor (approximately 0.27-0.31 m below the ceiling). The temperatures are far below 950 K at this location in the hallway thus the decrease in the CO and UHC levels is due to dilution from the cooler oxygen containing gases below. The lower-layer gases contain high concentrations of CO and UHC since all of the upper-layer gases do not escape the hallway and a sizable fraction is forced to recirculate back up the hallway toward the compartment.

4.0 RESULTS OF WINDOW EXPERIMENTS

To accurately monitor the gas flow into and out of the compartment, the air entrainment entrance into the compartment and the combustion gas exit from the compartment were separated in the manner shown in Fig.2; referred to as the window experiments.

The mass flow of the air entrained into the compartment was regulated using different size orifices as mentioned in section *2.2*. The velocity profiles of the air flowing in the duct with different diameter orifices attached is seen in Fig. 9. The profiles appear to be those of a fully-developed, turbulent flow and are very similar shape. The Reynolds numbers in the duct for orifice diameter was determined using the average velocity, denoted in Fig. 9 by the vertical lines, and was found to range from 9675 to 3425. With the radial location of the average velocity at approximately the same location for orifice diameters greater than 0.15 m, the velocity probe (located 10 duct diameters downstream of the orifice) was kept at the same radial location during all experiments.

The size of the window through which the gases exit the compartment was also varied. Window areas of 0.12, 0.08, and 0.04 m^2 were used in the experiments to vary both the fluid mechanics of the exhaust gas plume from the compartment and the global equivalence ratio inside the compartment.

Sampling was initially performed downstream of the hallway to identify the overall effects for different geometric and stoichiometric conditions. Sampling was then done inside the facility (both in the hallway and the compartment) to investigate the behavior of the combustion gases as they are produced, transported and oxidized under favorable conditions.

4.1 Downstream Sampling

To quantify the overall oxidation which occurs in the hallway as the combustion gases from the burning compartment are being transported down the hallway, sampling was done downstream of the compartment. These experiments were done first to get an understanding of how the fire behaves under a variety of physical and chemical conditions and to determine the situations (i.e. fuel pan diameter, orifice diameter, window size) where hallway sampling was necessary for the understanding of how the gases evolve within the hallway.

The yield of CO transported downstream of the compartment correlated quite well with the global equivalence ratio (GER) within the compartment, see Fig. 10. The points on the plot which are open with dots are from experiments where the end of the hallway was not blocked. These yields, as was seen by Ewens (1994) in his experiments, do not correlate well with the global equivalence ratio. An explanation for this is provided in the next section. The shape of the curve is similar to that of the CO yield versus global equivalence ratio curve inside the compartment determined by Gottuk (1992). It should be noted at this time that the compartment temperatures and the temperatures within the hallway never rose above 1100 K which is within the temperature range where the global equivalence ratio concept is valid, (Bryner et al., 1995). The data points contained in Fig. 10 are representative of experiments containing all soffit heights, fuel pan diameters, orifice diameters and window sizes mentioned previously in section *2.2*.

The plot of CO yield versus GER can be divided into three regions: overventilated, transitional and underventilated. In the overventilated region, $0<\phi<0.6$, an undetectable amount of CO is transported downstream of the compartment. This is expected since there is virtually no CO being produced inside the compartment in this GER range. Characteristic of the transitional region, $0.6<\phi<2.0$, is a steep rise in the CO yield with an increasing GER. The slope of the rise depends on whether or not external burning occurs within the hallway. The slope is 0.16 with no external burning and 0.11 with external burning. The region is broader and the rise in the CO yield is less steep compared to the in-compartment data taken by Gottuk (1992) where the transitional region was $0.6<\phi<1.5$ and the slope was 0.24. The underventilated region encompasses all $\phi>2.0$. The CO yields plateau in this region and remain fairly constant. The level at which the plateau occurs depends again on whether or not external burning is occurring inside the hallway. The CO yield averages 0.22 with no external burning and 0.16 with external burning. The plateau level with no external burning is consistent with the in-compartment results seen by Gottuk (1992). Overall, it appears as if the external burning resulted in a fairly consistent drop in the CO yield (0.05-0.06) for all GER greater than 1.2. Thus, the CO yields for the external burning case are simply the non-external burning yields shifted down by a CO yield of 0.05.

Curve fits to the data give rise to an equation which predict CO yield,

$$CO_{yld} = \frac{0.16}{\left[1+\left(\phi/1.51\right)^{-6.6}\right]} \quad (5),$$

with external burning occurring in the hallway and an equation which predicts the downstream CO yield,

$$CO_{yld} = \frac{0.22}{\left[1+\left(\phi/1.42\right)^{-4.5}\right]} \quad (6),$$

with no external burning in the hallway. To save on computational time in computer codes, the CO yield could also be estimated as a ramp function

$$CO_{yld} = \begin{cases} 0, \phi < 0.6 \\ b\phi - d, 0.6 < \phi < 2.0 \\ c, \phi > 2.0 \end{cases} \quad (7)$$

where;

b=0.11, d=0.06, and c=0.16 with external burning

b=0.16,d=0.10, and c=0.22 with no external burning

The downstream UHC yield is not predicted as well by the GER inside the compartment when external burning is not occurring but is predicted fairly well when it is occurring. The UHC data for experiments where external burning is occurring also forms a "S"-shaped curve when plotted against the GER, Fig. 11. Thus, the curve fit to the UHC yield data,

$$UHC_{yld} = \frac{0.054}{\left[1+\left(\phi/1.8\right)^{-6.5}\right]} \qquad (8),$$

takes a form similar to that seen in the curve fits for CO previously seen. It is interesting to notice that the UHC levels are not at a detectable level until a GER of approximately 1.5. The lack of UHC in the $0.6<\phi<1.5$ is due to the majority of the UHC being oxidized inside the hallway during external burning. The transitional portion of the UHC curve is $1.5<\phi<2.25$ and has a slope of approximately 0.072. The UHC yield plateaus at 0.054 for $\phi>2.25$. Again, the UHC yield downstream when external burning is occurring in the hallway can be estimated using a ramp function

$$UHC_{yld} = \begin{cases} 0, 0<\phi<1.5 \\ 0.072\phi - 0.11, 1.5<\phi<2.25 \\ 0.054, \phi>2.25 \end{cases} \qquad (9).$$

From these experiments, the amount CO which can possibly be transported downstream of the compartment has been quantified and correlated to the GER. The CO can be estimated by the curve fit to the data or by using a simple ramp function. The most significant phenomena which affects the amount of CO transported downstream is the occurrence of external burning. Hallway sampling will be performed to verify that the window size and the addition of a 0.20 m soffit height does not have a significant effect on the levels of CO transported down the hallway. Sampling will also be performed in the hallway to study the transport of gases down the hallway when no external burning occurs.

4.2 In-Hallway Sampling

4.2.1 Upper-Layer Variations

Hallway sampling was done for four situations which contained different geometric conditions at the hallway entrance but similar compartment global equivalence ratios; all are listed in Table I. A fifth set of hallway experiments was performed with a slightly higher global equivalence ratio to investigate the non-external burning case with a 0.20 m soffit at the hallway entrance. The most extensive data set, by far, is the external burning case with a 0.20 m soffit at the hallway entrance. Since, the gas concentrations in the upper-layer for all the cases which contained external burning are very similar, the most extensive data set will be presented first. The data sets where external burning occurred in the hallway when no soffit was present at the hallway entrance will then be explained followed by the two data sets in which no external burning occurred in the hallway. All data presented is taken 0.05 m below the ceiling of the hallway. The only exception to this was when a 0.20 m soffit was present at the hallway entrance. In this case, sampling was performed at 0.25 m below the ceiling at the window and 0.15 m below the ceiling 0.30 m across the hallway. These two sampling locations were performed to measure the concentrations in the plume exiting the compartment and rising to the hallway ceiling.

Table I. Experimental conditions for hallway sampling study.

Window Area, m^2	Soffit Height,m	Fuel Pan Dia., m	Orifice Dia., m	GER, ϕ*	Q, kW*	Time to Flashover, seconds**	External Burning (Yes/No)	No. of Exp.
0.12	0.0	0.20	0.20	2.73	446	263	Yes	12
0.08	0.0	0.20	0.20	2.98	425	256	Yes	10
0.04	0.0	0.20	0.30	3.34	364	236	No	14
0.04	0.20	0.20	0.25	3.21	382	249	Yes	25
0.04	0.20	0.20	0.15	3.53	314	230	No	4

*Values are taken from a 10 second average of a window of data starting 20 seconds after flashover.
**Flashover time was estimated by the time where a steep rise in the GER was noticed (when $\phi>1.5$).

Before showing the quantitative variations of the species concentrations and temperatures inside the facility, a qualitative explanation of the changes occurring in the overall conditions in the facility during the course of a fire will be given. This description is based upon visual observation and video records. The pool of hexane in the compartment is ignited. The combustion gases from the pool fire fill the compartment upper-layer, and begin escaping the compartment through the window into the hallway. The gases proceed across the hallway and impinge upon the wall opposite the compartment. The bulk of the combustion gases then move down the hallway along the corner of the ceiling and the side wall opposite the compartment entraining gases inside the hallway along the way. As the gases reach the end of the hallway, some escape through the 0.20 m high, 1.22 m wide opening at the end wall and are collected by a fume hood. The gases which do not escape follow along the wall at the end of the hallway traveling back across the hallway. These gases then migrate back down the hallway along the wall which contains the window connecting the compartment and the hallway. As the fire builds up in the compartment, the upper-layer in the hallway becomes more highly concentrated in combustion gases while oxygen levels in the upper-layer fall. As flashover occurs inside the compartment, a thick upper-layer (which later will be shown to be greater than 0.50 m deep) containing oxygen concentrations of approximately 9-12% is present in the hallway. During the post-flashover stage of the compartment fire, the hallway gases, in the majority of the experiments, are able to ignite resulting in external burning within the hallway for approximately 80-100 seconds. When external burning does not occur in the hallway, a mixture of gases containing high concentrations of CO and UHC continues to build up in the hallway upper-layer. Near the end of the experiments with no external burning, flashover occurs in the hallway (the upper-layer along the entire length of the hallway instantly ignites). This was visually observed from a monitor inside the data acquisition building. The pool fire then depleted the fuel contained in the pan and extinguished.

4.2.1.1 Experiments with External Burning

The most extensive hallway data set with external burning occurring in the hallway was generated with a 0.20 m soffit at the hallway entrance and a 0.04 m^2 window connecting the hallway and the compartment. A total of 25 experiments were performed with sampling being done at 23 different locations in the hallway and at 2 locations in the compartment upper-layer all indicated in Fig.12. With temporal data of species concentrations and temperatures at a variety of locations, a picture of the variation in concentrations and temperatures in the hallway upper-layer could be seen. The wet species concentrations and temperature levels (not normalized to the values given in section **2.2**) shown in the contour plots were generated by averaging over a ten second period at particular time increments which are listed in terms of time after flashover (i.e., the flashover time was time t=0). Negative times are compartment pre-flashover results and positive times represent post-flashover results. The back of the compartment in the contour plots is the location of the origin of the y-axis. The x-axis begins at 0.76 which is the center of the window (0.76 m down the hallway from the dead end wall) connecting the compartment to the hallway. Except for the exit of the hallway, the limits of the contour plots inside the graph corresponds to walls in the hallway and the compartment. The end of the hallway where gases are eventually collected in the fume hood located is actually 5.1 m downstream. All of the CO contour plots show the sampling locations seen previously in Fig. 12 on the actual graph.

As expected, there is a nearly undetectable amount of CO present in the hallway during pre-flashover, but this rapidly changes with the occurrence of flashover. During the 10-20 second time interval after flashover has occurred inside the compartment, gases containing high concentrations of CO begin to creep out of the compartment and across the hallway, see Fig. 13. The UHC levels seen during this time interval are accumulating in the upper-layer of the compartment, but only low concentrations are being transported outside of the compartment, see Fig. 14. The 10-20 second time interval is just prior to the occurrence of external burning in the hallway. This is evident through the concentrations of CO_2 and O_2, see Fig. 15 and Fig. 16 respectively. The CO_2 concentrations are greater than 10% inside of the compartment while lower CO_2 concentrations, 4-8%, in the hallway upper-layer is evidence that no external burning is occurring. The high levels of O_2 (8-12 %) also supports the visual observations of no external burning during this time interval, see Fig. 16. The gases exiting the compartment are entraining hallway gases which contain low concentrations of O_2, approximately 8%, much lower than the 21% observed in ambient air. The O_2 distribution in the hallway displays an area (y=0.9 m and x=1.4-4.6 m) of high O_2 concentration. The vortical structure traveling along the corner of the wall opposite the compartment and the ceiling (where low levels of O_2 are present) pulls high O_2 concentration gases from the lower-layer in the hallway. The high O_2 concentrations at the bottom right corner of the hallway are due to ambient air entering the hallway through the opening in the mostly blocked end of the hallway. The temperatures are approximately 550 K throughout the hallway, see Fig. 17, which again is evidence no external burning is occurring in the hallway.

External burning occurs in the hallway for these experiments approximately 20-30 seconds into the post-flashover period. The external burning in the hallway was not attached to the compartment window, but instead was seen to start burning after the gases had traveled approximately half way across the hallway. This type of burning where the flame is not attached to the window has been seen to result in inefficient oxidation of CO giving rise to higher yields of CO downstream (Gottuk, 1992). The flame was seen to impinge upon the wall opposite the compartment and travel in a clockwise swirling motion along the corner of the ceiling and the side wall. The flame was visually seen to extend down the hallway approximately 2.5-3.0 m from the dead end wall.

After just 30-40 seconds into the post-flashover period, external burning is beginning to occur in the hallway and a stream of gases containing high concentrations of CO is seen traveling across the hallway and along the wall opposite the room, see Fig. 18. The UHC are seen to oxidize very effectively as they move across the hallway, see Fig. 19. A significant increase in the levels of CO_2 in the hallway to approximately 10% with O_2 levels dropping in the 2-3% range are indicators that external burning is occurring in the hallway, see Fig. 20 and Fig. 21 respectively. It is evident through the unorganized distribution of the gases in the hallway upper-layer that the hallway is in a transient period. Gas temperatures remain near 550 K except for those gases moving across the hallway, see Fig. 22.

In the 50-60 second time interval during post-flashover, CO concentrations as high as 1.6% are seen escaping the hallway on the side of the hallway opposite the room despite the presence of external burning in the hallway, see Fig. 23. These concentrations of CO are seen to follow along the end wall and recirculate back down the hallway toward the compartment beside the wall containing the window of the compartment, see Fig. 23. The CO concentration on the side of the hallway where the compartment is located remain at concentrations less than 0.75%. The oxidation of CO is being limited by the oxidation of the UHC. While the gases are near the compartment (where they are at their highest temperatures), the UHC are being oxidized instead of the CO, see Fig. 24. Levels of CO_2 and O_2 are very uniform within the hallway, see Fig. 25 and Fig. 26, suggesting the hallway upper-layer is beginning to come to an equilibrium. The high temperatures in the hallway (seen as green in Fig. 27) are synonymous with the location of where the external burning was visually observed.

A low concentration cell of CO 2.0 to 4.0 m down and 0.7-1.0 m across the hallway is apparent in the 70-80 second time interval during post-flashover, see Fig. 28. This region is located beside the swirling flame which is seen traveling in the corner of the ceiling and the wall down the hallway. The low concentrations of CO may be a result of sampling just outside of the flame traveling down the hallway, but data suggests it may be more due to the fluid mechanics in the hallway. The CO_2 variation in the hallway before external burning, see Fig. 15, is similar to the distribution of CO during this time interval suggesting that the low cell of CO seen in Fig. 28 is a result of the vortical structure pulling lower-layer gases into the upper-layer. On the side of the hallway where the compartment is located, the effects of a portion of the gases not leaving the hallway and recirculating back down the hallway to the compartment is becoming evident.

During the 70-80 sec time interval after flashover, the levels of UHC in the hallway are highest near the compartment where the gases are entering and moving across the hallway, see Fig. 29. By the time the gases have started to move down the hallway along the wall opposite the compartment, the UHC are seen to diminish to concentrations 10 times less than those concentrations entering the hallway. Thus, it appears that the external burning is depleting the hallway gases of UHC, but the CO concentrations are not falling significantly. The upper-layer of the entire hallway contains a uniform distribution of approximately 10% CO_2 and 0.5% O_2, see Fig. 30 and Fig. 31 respectively. No significant production of CO from CO_2 is apparent due to the temperatures being much lower than 1100K where the water gas shift reaction comes into equilibrium which would favor the formation of CO from CO_2 (Pitts, 1992). Figures 31 and 32 give further insight on why high levels of CO are being transported. Gases from the compartment containing virtually no O_2 enter the hallway where O_2 concentrations do not exceed 3.0%, see Fig. 31. The oxygen which does get entrained into the gases exiting the compartment is mostly being used to oxidize UHC. The temperature levels in the hallway also prevent efficient CO oxidation since typical temperatures in the upper-layer are at the lower end of where CO oxidation takes place readily (850-925 K), see Fig. 32. These temperatures only persist until the gases have traveled approximately 2.2 m down the hallway at which time they rapidly decrease in level. The high temperature region corresponds, approximately, to the location where the external burning was visually seen to be present in the hallway. The low temperatures near the end of the hallway are due to the combustion gases cooling after recirculating along the end wall containing the opening. The gases are reheated as they are transported back toward the compartment.

The structure of the cell in the upper-layer is still apparent in the 100-110 second time interval while the CO concentrations in the hallway continue to rise, Fig. 33. With the levels of CO in the compartment beginning to decrease, see Fig. 33, the pool fire inside the compartment is running out of fuel. Shortly after this time interval, external burning in the hallway ceased and the pool fire inside the compartment extinguished upon the depletion of the fuel in the pan.

The contours of the CO_2 and O_2 indicate the upper -layer gases near the hallway exit are being diluted during the 100-110 second interval while the UHC and temperature contours remain approximately the same. The weaker external burning is occurring inside the hallway resulting in the oxidation of the UHC, see Fig. 34. The weakening of the compartment fire during this time interval is noticed by a fall in both the CO and UHC levels inside the compartment, see Fig.33 and 34., respectively. It is also noticeable in the hallway through the CO_2 and O_2 contours. The CO_2 concentrations in the hallway upper-layer are becoming diluted, see Fig. 35, by the apparent entrainment of O_2 from the lower portion of the hallway and air entering through the 0.20 m high, 1.22 m wide opening, see

Fig. 36. This is highly possible since the gases from the compartment are traveling down the hallway in a swirling motion pulling lower-layer gases into the upper-layer. The gases which recirculate back toward the compartment appear to be entraining some ambient oxygen through the opening where the gases exit the hallway. It is interesting to note that the CO inside the hallway for this time interval actually increased from the 70-80 second interval despite the fact that higher O_2 and lower CO_2 concentrations are observed. The external burning in the hallway gives rise to temperatures which are approximately the same as those seen in the 70-80 second interval, see Fig. 37.

The distribution of the different species concentrations in the hallway for experiments where external burning occurred in the hallway with and without a soffit at the window are very similar as the gases move across the hallway, but differ slightly in the levels in the middle of the hallway. To demonstrate this point, the variation in the species concentrations and the temperatures in the hallway during the 70-80 second time interval from the experiments with a 0.20 m soffit and a 0.04 m^2 window (open symbols with dashed lines) were compared to those experiments with no soffit and a 0.08 m^2 window (closed symbols with solid lines). The 70-80 second time interval was chosen since the upper-layer in the hallway has sufficient time to develop and reach a quasi-steady state. Sampling was performed at locations B,C,T,I,K-N shown in Fig. 12. The variations in the temperatures and concentrations of the species as they move across the hallway, locations B,C,I,&T, are nearly the same in shape and magnitude except for the UHC, Fig. 38a. The UHC are being reduced through oxidation as they travel across the hallway while the CO levels are remaining constant and equivalent to the levels with no soffit. It will be seen in the next section, that the more effective oxidation of the UHC is due to the increased entrainment of oxygen into the combustion gases exiting the compartment. The inefficient oxidation of the UHC keeps the temperatures low which in turn causes the oxidation of CO to be inefficient and virtually nonexistent.

After the gases impinge upon the wall, they begin to travel down the hallway. The variation in the species was studied by sampling at locations T,K-N. Experiments with the 0.08 m^2 window showed a slightly higher concentration of O_2 downstream resulting in lower concentrations of CO and CO_2 downstream along the center of the hallway, see Fig.

Table II. The unit momentum of the jet of the gases entering the hallway from the compartment.

Entrance Soffit Height, [m]	Window Area, A, [m^2]	Density of Gases*, ρ, [kg/m^3]	Mass Flow of Gases, $\dot{m}$ [kg/s]	Unit Momentum, M', [N]
0.0	0.12	0.3666	0.066	0.100
0.0	0.08	0.3666	0.50	0.111
0.0	0.04	0.3666	0.45	0.138
0.20	0.04	0.3666	0.57	0.170

*Values based on the density of air at the gas temperature at the hallway entrance

38b. The discrepancy in the two data sets downstream of the compartment is attributed to the differences in both the entrance soffit height and the window size, but more due to the soffit height. Through estimating the velocities exiting the compartment for both cases, a rough estimate of the unit momentum of the jet of the gases entering the hallway,

$$M' = M/l = \frac{\dot{m}^2}{\rho A} \qquad (10),$$

can be obtained. These estimates are seen in Table II.

The momentum of the gases entering the hallway is highest in the case with a 0.20 m soffit. The 0.20 m soffit allows the gases exiting the compartment to buoyantly rise until they impinge upon the ceiling. This impingement results in a loss in the momentum of the gases before they impinge on the wall opposite the compartment. In the absence of a soffit at the hallway entrance, the gases from the compartment travel along the ceiling and do not experience a significant loss until they travel across the hallway and impinge on the side wall. Thus, the gases with no soffit have more momentum when reaching the side wall opposite the compartment, causing the location of the low CO concentration cell seen in Fig. 28 and Fig. 33 to be shifted more toward the middle of the hallway. The fact that the species concentrations moving across the hallway for the two cases are virtually the same in magnitude and shape negates the possibility that the GER of the combustion gases as being the cause of the discrepancy, see Fig. 38a. Since the downstream yields are nearly constant for cases with external burning (whether or not a soffit is present at the hallway entrance), the average concentration of the gases exiting the hallway is assumed to be nearly the same for all cases with external burning.

4.2.1.2 Experiments with No External Burning

External burning did not occur in some experiments with the 0.04 m^2 window. Only a limited number of these experiments were performed since the variation in the concentration of the gases in the hallway was not expected to be large. In experiments with no soffit (closed symbols with solid lines), the sampling was performed at locations B,C,T and I-N while sampling was performed at locations C,T,W and Y when a 0.20 m soffit (open symbols with dashed lines) was present.

In both cases, the gases exit the compartment and migrate across the hallway with the concentration of CO, UHC and CO_2 decreasing from the dilution of the compartment fire gases with the gases contained in the hallway, Fig. 39a. The compartment gases in the experiments with a 0.20m soffit are diluted more effectively compared with the case with no soffit by the time the gases have traveled to the opposite side of the hallway. This is evident by the presence of a higher concentration of O_2 at this location. After the gases hit the side wall and turn to begin moving down the hallway, the concentration of the gases remain relatively constant when sampling in the middle of the hallway (as was done in the case with no soffit), see Fig. 39b. When sampling down the hallway near the wall across from the compartment, the gas concentrations also remain relatively constant. Slightly higher levels of CO, UHC and CO_2 with lower concentrations of O_2 are seen along the side wall compared to the locations in the middle of the hallway. This is expected since this is where the flow of the most recent compartment fire gases is present. Most importantly, the CO level leaving the hallway was 1.6-1.9%. This level of CO is fatal after an exposure time of approximately 3 and a half minutes.

4.2.2 Lower-Layer Variations

In the experiments with a window size of 0.12 m^2 and 0.04 m^2 when no soffit was present at the hallway entrance, sampling was done at location L, see Fig.12, as far as 0.50 m below the ceiling. Upper-layer profiles during the 70-80 second time interval after flashover will be shown for the two window sizes.

With a 0.12 m^2 window connecting the compartment to the hallway, external burning occurs and the upper-layer along the middle of the hallway takes the form seen in Fig. 40. At approximately 1.3-1.4 m above the floor (0.35-0.25 m below the ceiling), a decrease in the oxygen levels is observed. This is attributed to the swirling gases traveling down the hallway forcing higher concentrations of combustion gases into the lower portion of the hallway. Through visual inspection, the vortex traveling down the hallway does not extend into the lower-layer of the hallway any lower than what was sampled. Therefore, the O_2 concentration should increase significantly the closer the sampling is done toward the floor.

No external burning occurred in the hallway with a 0.04 m^2 window. The species concentrations in hallway upper-layer are quite uniform until 1.30 m above the floor (0.35 m below the ceiling), see Fig. 41. At this point, the CO, CO_2 and UHC all begin to become diluted by the oxygen rich lower-layer. The temperatures are also uniform over the entire height of the scan.

4.3 Prediction of External Burning

From the downstream (exhaust duct) and in-hallway results, higher CO levels were transported when external burning did not occur in the hallway. The prediction of external burning within the hallway was attempted using the ignition index,

$$I.I. = \sum_i \frac{X_i \Delta H_{c,i}}{\int_{T_o}^{T_{SL,i}} n_{prod} C_p dT} \tag{11}$$

where;

X_i is the mole fraction of the species i
$\Delta H_{c,i}$ is the heat of combustion of the species i, kJ/g-mole
$T_{SL,i}$ is the adiabatic flame temperature stoichiometric mixture for fuel species i, K
T_o is the temperature of stoichiometric mixture prior to reaction, K
n_{prod} is the number of g-moles of products of complete combustion per g-moles of reactants
C_p heat capacity of products of complete combustion, kJ/g-mole K

which was defined by Beyler (1984). When the ignition index goes above 1.0, the gases are predicted to ignite. The ignition index was applied to experiments where gases were sampled in the middle of the window, location C in Fig. 12.

Two experiments were used to determine whether the ignition index could predict the occurrence of external burning. The experiment where external burning occurred contained a 0.08 m^2 area window with a GER of approximately 2.75. The experiment where no external burning occurred in the hallway contained a 0.04 m^2 window with a GER of approximately 3.0.

The ignition index for the external burning case, seen in Fig. 42a, predicts that external burning will occur in the hallway at approximately 300 seconds which is the same time they were visually seen to ignite. For the experiment without external burning in the hallway, the ignition index predicted external burning would occur at approximately 300 seconds where it was seen to rise above 1.0, Fig. 42b.

The ignition index assumes a pilot ignition source is present at the window. Since the concentrations of the gases entering the hallway were nearly the same in both cases, the inability of the ignition index to predict the ignition of the gases was attributed to the reduction in the ignition source of the gases (i.e. the window size). With the smaller window size, less heat is transferred to the hallway from the compartment (both through convection and radiation). Experiments have not been performed to attempt to ignite (using an external ignition source) the gases exiting the window.

4.4 Vitiated Hallway Upper-Layer

From the experimental results presented thus far, it is difficult to determine whether the transport of high concentrations of CO was made possible by either the entire hallway being oxygen deficient or by the hallway upper-layer being oxygen deficient. From the vertical profiles described in section ***4.2.2***, the oxygen concentration was approximately 11% just 0.40 m below the ceiling in the hallway experiments with and without external burning. It appears that the lower portion of the hallway contains concentrations of O_2 nearly equal to that observed in ambient air. Thus, it was hypothesized that CO could be transported if a sufficiently thick, oxygen deficient upper-layer was present in the hallway when the compartment reached flashover. It was speculated that if the upper-layer had reached this critical thickness where CO was being transported, the lower-layer could be filled with ambient air and high concentrations of CO would still be able to be transported to remote locations.

The theory was experimentally tested by replacing the wall which limited the ambient air entrainment into the hallway with a 1.10 m soffit at the hallway exit. With this arrangement, ambient air entrained into the lower portion of the hallway through a 0.57 m high, 1.22 m wide opening at the exit of the hallway. A 0.20 m diameter fuel pan was present in the compartment with a 0.08 m^2 window connecting the compartment to the hallway. The sampling was done near the exit of the hallway (at location X seen in Fig.12) 0.05 m below the ceiling.

The temporal variations in the different species concentrations near the exit of the hallway are shown in Fig. 43. During the compartment pre-flashover time, the upper-layer in the hallway develops increasing concentrations of combustion products. No smoke was visually seen to exit the hallway until nearly 200 seconds into the experiment. By the time flashover was reached in the compartment (approximately 340 seconds), the upper-layer in the hallway was quite O_2 deficient. At the sampling location near the exit of the hallway, the O_2 concentration at flashover was approximately 7% while the CO_2 concentration was approximately 8%. Only 60 seconds after flashover occurred inside the compartment, the levels of CO and UHC reached a quasi-steady state value of approximately 2.0% and 3.2%, respectively. These levels persisted for nearly 100 seconds before declining upon the extinguishment of the fire inside the compartment. During the course of the entire experiment, no external burning was observed to be present in the hallway and hallway was permitted to entrain ambient air into the lower portion of the hallway. This experiment, therefore, has shown CO can be transported in high concentrations to remote locations from the compartment with a hallway which contains ambient air in the lower portions of the hallway.

5.0 SUMMARY AND CONCLUSIONS

The experiments where a limited amount of air was allowed to entrain into both the hallway and the compartment resulted in conditions which were conducive for the transport of high concentrations of CO to locations remote from the burning compartment. The amount of CO, in terms of yield, which gets transported to these remote locations was correlated to the GER inside the compartment. With the GER>2.0, the CO yield averages 0.16 when external burning is occurring in the hallway and 0.22 with no external burning in the hallway. With external burning, CO was exiting the hallway at concentrations as high as 1.6%; a level which is fatal to humans after an exposure time of slightly more than 4 minutes. The external burning in the hallway did, however, burn off nearly all of the UHC before the gases had traveled across the hallway. The experiments where no external burning occurred in the hallway CO traveled out of the hallway at concentrations as high as 1.9% which would cause death after only 3 minutes of exposure.

With the compartment in the post-flashover stage and external burning occurring in the hallway, high concentrations of CO were seen to travel out of the compartment and across the hallway. High concentrations of CO then traveled down the hallway along the wall opposite the compartment. The wall blocking the majority of the end of the hallway forced some of the gases to recirculate back down the hallway toward the compartment. This caused higher levels of CO to begin to accumulate in the upper-layer of the hallway. Thus, a steep gradient in the CO concentration existed across the hallway with the highest concentrations traveling in the corner of the ceiling and side wall on the opposite side of the hallway from the compartment. Therefore, with the compartment-hallway configuration shown in Fig. 2, caution should be used when assuming the CO levels are uniformly distributed across the hallway ceiling at locations near the burning room.

The extent to which CO was oxidized in the hallway was not drastically affected by the window size connecting the compartment and the hallway or by the soffit size at the window. This was attributed to the plume of gases exiting the compartment being forced to entrain oxygen containing combustion gases in the hallway upper-layer and not ambient air. This results in the oxidation of the majority of the UHC with only a limited oxidation of CO. Since the UHC have a higher rate of oxidation, and utilize the majority of the limited O_2 available to the compartment gases. By the time the UHC have been sufficiently oxidized allowing the CO to begin oxidizing, the gas temperatures have cooled to a point where CO oxidation does not occur readily.

The ignition index was examined as a tool to predict when external burning would occur in the hallway. It was able to predict the occurrence of external burning in the case where external burning occurred in the hallway. However, the ignition index predicted external burning in the hallway in high GER experiments with no external burning. Thus, the ignition index was able to predict whether the mixture exiting the compartment was flammable, but it was unable to unconditionally predict the ignition of this mixture. Since the ignition index assume a pilot ignition source to be present, the failure of the ignition index was attributed to the lack of an ignition source from the compartment with a smaller window size (0.04 m^2) where external burning was not seen to occur in the hallway.

To determine whether the CO oxidation is dependent on the entire hallway being oxygen deficient or simply on the upper-layer in the hallway being oxygen deficient, an experiment was performed with a 1.10 m soffit at the hallway exit which allowed the entrainment of ambient air into the hallway through the 0.57 m high, 1.22 m opening below the soffit. The experiment resulted in CO being transported in a concentration of 2.0 % at a location 2.65 m down the hallway from the middle of the 0.08 m^2 window. During this experiment, ambient air was allowed to enter the hallway and no external burning was present.

From the experiments performed by Ewens (1994) and those presented here, the extent to which CO is oxidized inside the hallway is highly dependent on the thermodynamic conditions in the hallway upper-layer when the compartment has reached flashover. If the gases are entering a hallway filled with virtually all ambient air, the oxidation of CO depends on the geometric conditions at the hallway entrance (Ewens, 1994). As the upper-layer in the hallway (most importantly around the window of the compartment), prior to flashover in the compartment, contains lower O_2 levels, the plume entering the compartment entrains oxygen containing combustion gases. Under these conditions, the oxidation of CO appears to be inefficient and less sensitive to the geometric conditions in the hallway.

From these experiments, a number of conclusions can be drawn about the transport of CO.

- Limited air entrainment into the hallway is not necessary for the transport of high concentrations of CO to remote locations.
- The thermodynamic conditions of the hallway upper-layer, especially where the compartment gases enter the hallway, govern the oxidation of CO.
- CO oxidation is sensitive to the geometric conditions when the hallway upper-layer is over-ventilated, (Ewens, 1994).
- CO oxidation is poor and fairly insensitive to geometric conditions when the hallway upper-layer is under-ventilated.
- External burning in an under-ventilated upper-layer results in the oxidation of nearly all the UHC but the CO exits the hallway at a concentration of 1.6% (45% of the levels inside the compartment).
- No external burning in the hallway allows the transport of CO in concentrations of 1.9 %. This is 54% of the in-compartment levels which is similar to the percent reduction in the CO transported in the full scale experiments by Morikawa et al.(1993) and Nelson (1988).
- There appears to be a critical hallway upper-layer depth which allows the transport of high concentrations of CO to remote locations.

6.0 FUTURE WORK

During the course of the next year, the investigation will continue to concentrate on determining the conditions necessary for the transport of high concentrations of CO to locations remote from the fire source.

The initial part of the study will focus on determining the critical depth of the upper-layer in the hallway necessary for CO to be transported in high concentrations. The effects of the window size, global equivalence ratio, and the soffit at the window on the critical upper-layer depth will be investigated. The critical hallway upper-layer depth, δ_{cr}, will be related to the distance the bottom of the window is below the ceiling, ξ. Critical upper-layer depths for door openings will be determined using the neutral plan distance below the ceiling as ξ. The estimated upper-layer depth for a door opening will be experimentally verified by blocking off the plenum as seen in Fig. 3. The air entrainment into the hallway will be measured and compared with the estimates of air entrainment from the $AH^{1/2}$ relationship developed by Kawogoe (1958). The downstream CO yield will be correlated with the compartment GER.

The validity of the correlations of downstream yield with the compartment GER developed in the study presented here will be verified to hold in these experiments through a series of experiments with different GER, window sizes and soffit heights.

With the room on the side of the hallway, the hallway upper-layer was found to be quite non-uniform in concentration of CO. For the cases where the upper-layer in the hallway, δ, is equal to or greater than the critical upper-layer, the upper-layer within the hallway will be thoroughly mapped to determine the variation in the species concentrations. Species concentrations and temperatures will also be determined at various heights within the upper-layer to obtain a better knowledge of the contents of the entire upper-layer.

To investigate the concentration of hydrogen and of different hydrocarbons produced from the hexane pool fires, sample bags of combustion gases exiting the compartment into the hallway will be obtained. These sample bags of combustion gases will then be analyzed using a gas chromatograph.

The compartment will then be moved along the side wall from the end of the hallway to the middle of the hallway, Fig. 44. The critical hallway upper-layer depths will be experimentally tested to see if they hold for this compartment-hallway configuration. Again, the hallway upper-layer will be thoroughly mapped. The upper-layer variations for the side-end and the side-middle configurations will then be compared to determine the effect of the compartment-hallway configuration.

The present compartment will then be replaced by a compartment containing a door (which extends from the bottom of the soffit to the floor of the hallway). Air will enter the new compartment through the lower portion of the door while combustion gases will exit through the top portion of the door. The inflow and outflow from the compartment will be monitored to make it possible to determine the GER inside the compartment. The variation in species concentrations in the compartment upper-layer will initially be analyzed to characterize the behavior of the gases inside the compartment. Critical hallway upper-layer depths where CO is transported to remote locations will be estimated using previous results and verified through experimentation. Species concentration and temperature variations within the hallway upper-layer will be experimentally determined and compared with results from the experiments using the compartment with the window size opening.

7.0 PERSONNEL

Mr. Brian Y. Lattimer continues to work on the project as a graduate research assistant. Mr. Lattimer successfully completed his oral Preliminary Examination during May, 1995 making him a Ph.D. candidate. In addition to the research done during the past year, he has had the opportunity to present papers at 3 conferences and aid in the writing of a journal paper.

Mr. Lattimer was assisted by 3 undergraduate researchers, Mr. Matt Finn, Mr. Dan May and Mr. Jason Littleton, over the course of the past year. The undergraduate researchers have installed and made the hallway automated sampling cart operational. They also aided in installing an automatic ignition system and an access door to the compartment to increase the safety in operating the facility.

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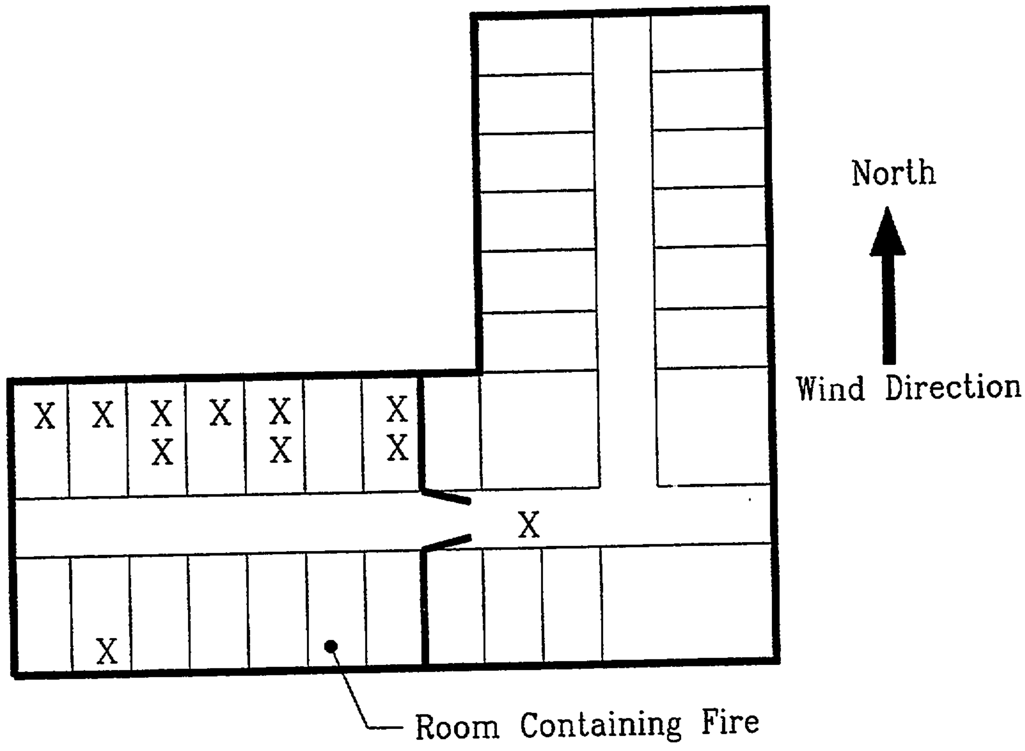


Figure 1. Locations of victims in Hillhaven Nursing Home fire.

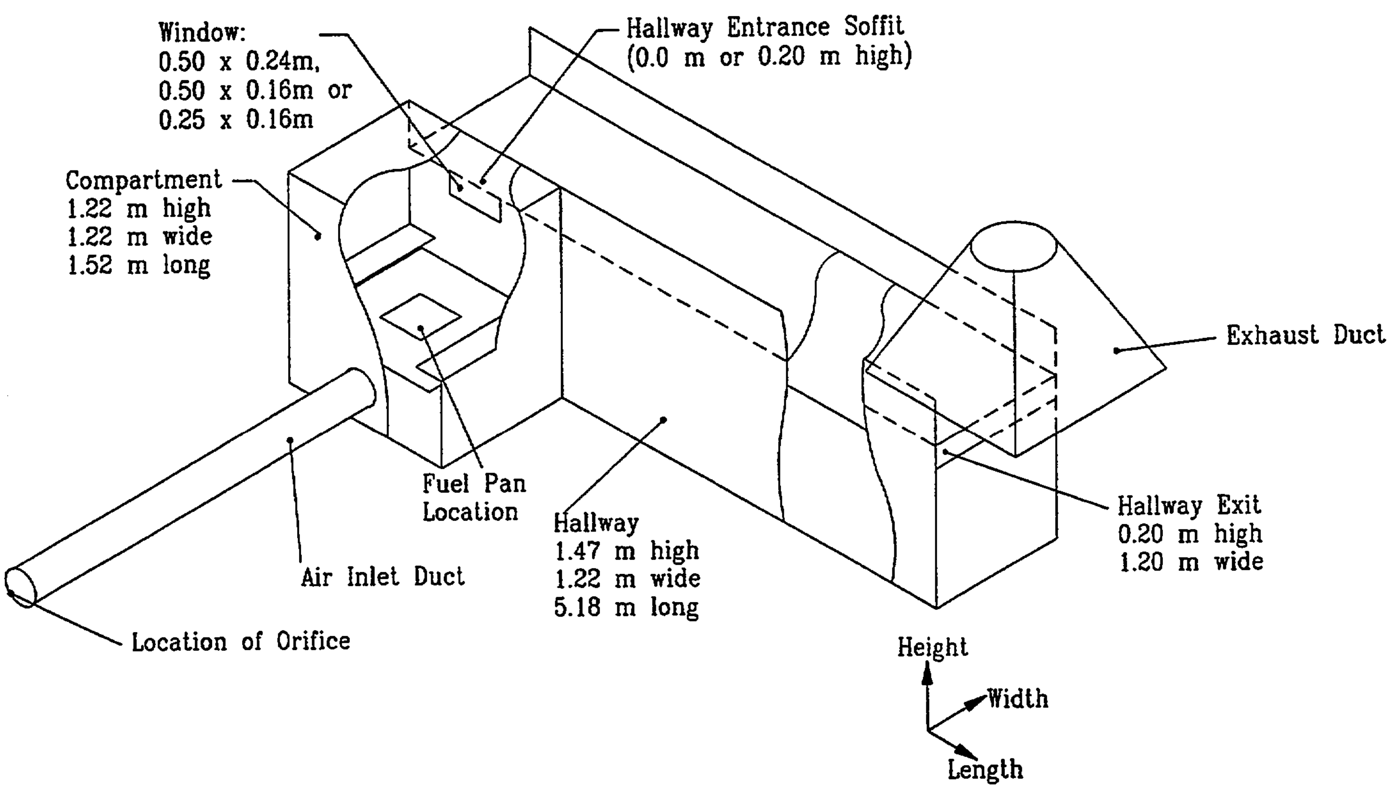


Figure 2. The side-end compartment-hallway configuration with a window connecting the hallway to the compartment

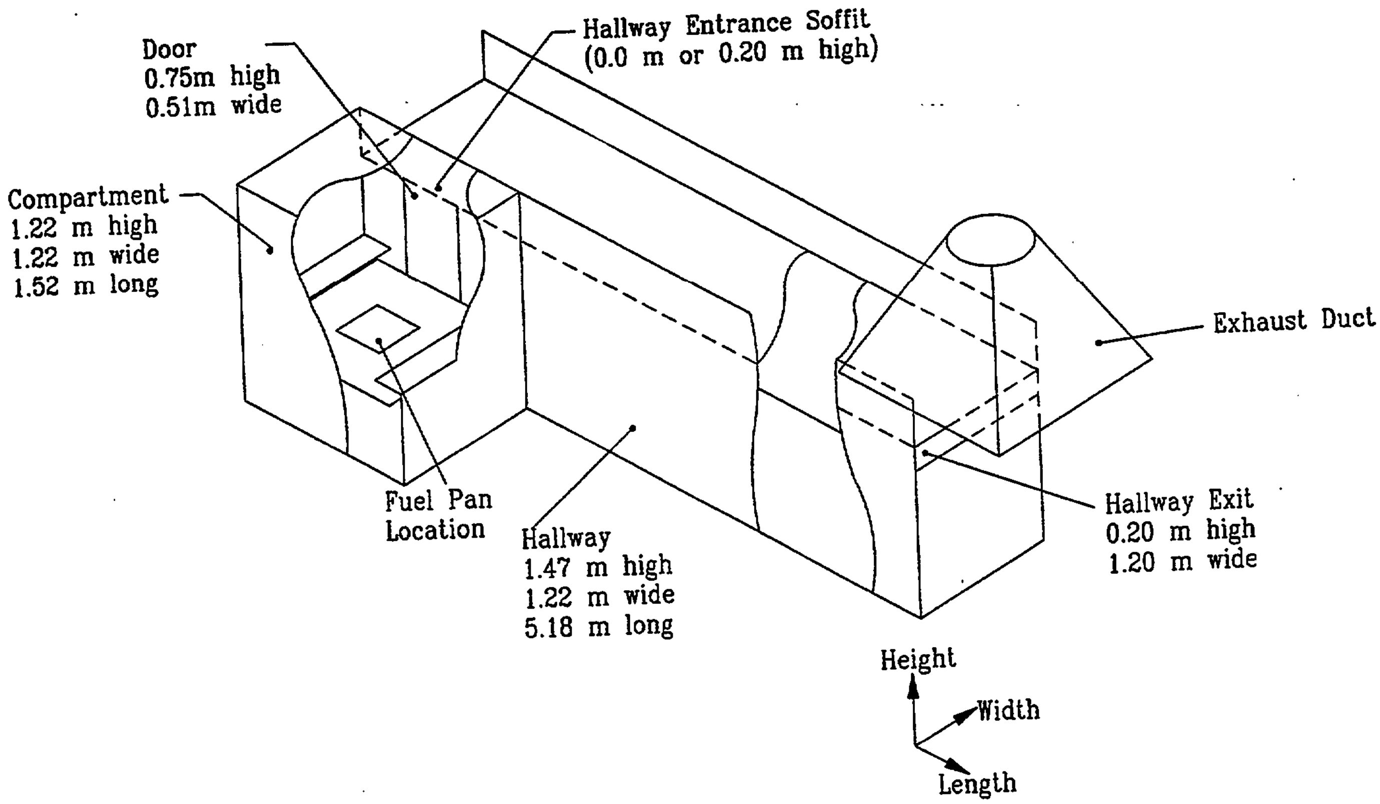


Figure 3. The side-end compartment-hallway configuration with a door connecting the compartment to the hallway and no air inlet duct.

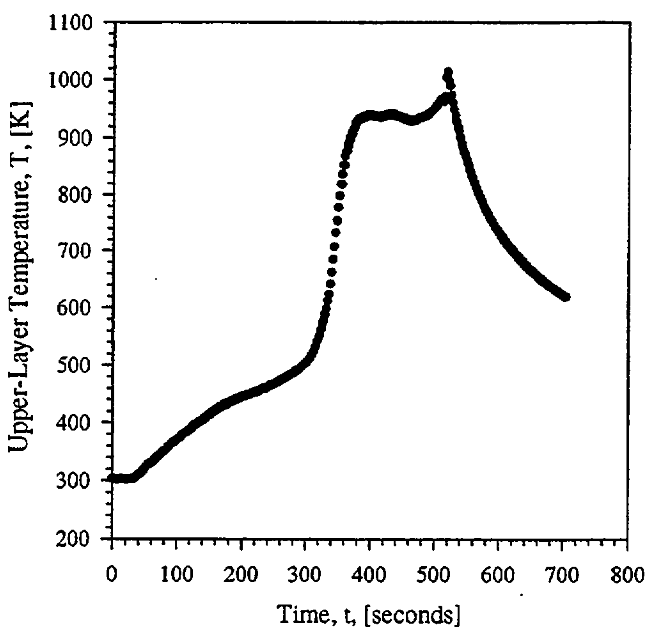


Figure 4. Temporal plot of the upper-layer temperature inside the compartment containing a door.

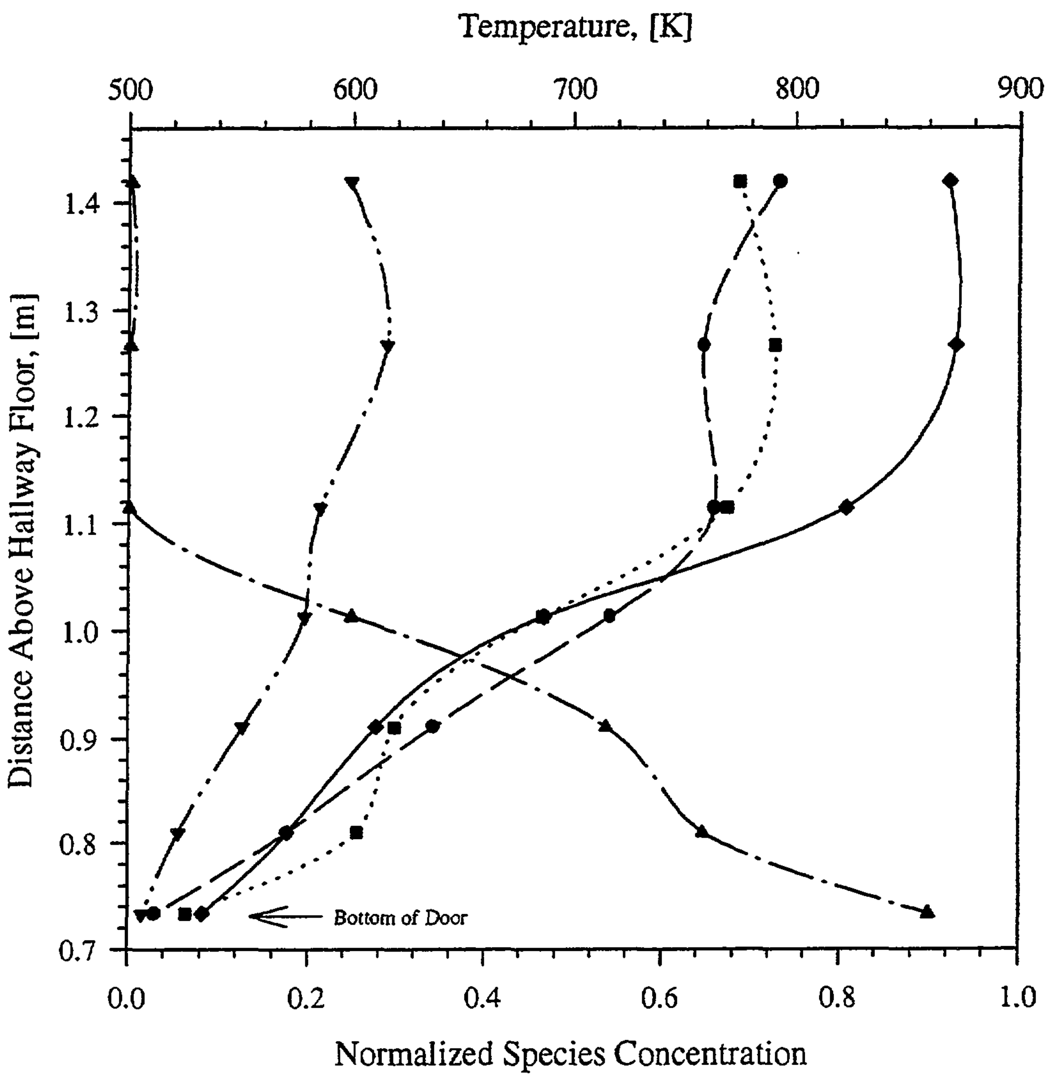


Figure 5. The variation in the species concentrations and temperatures at the door. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.

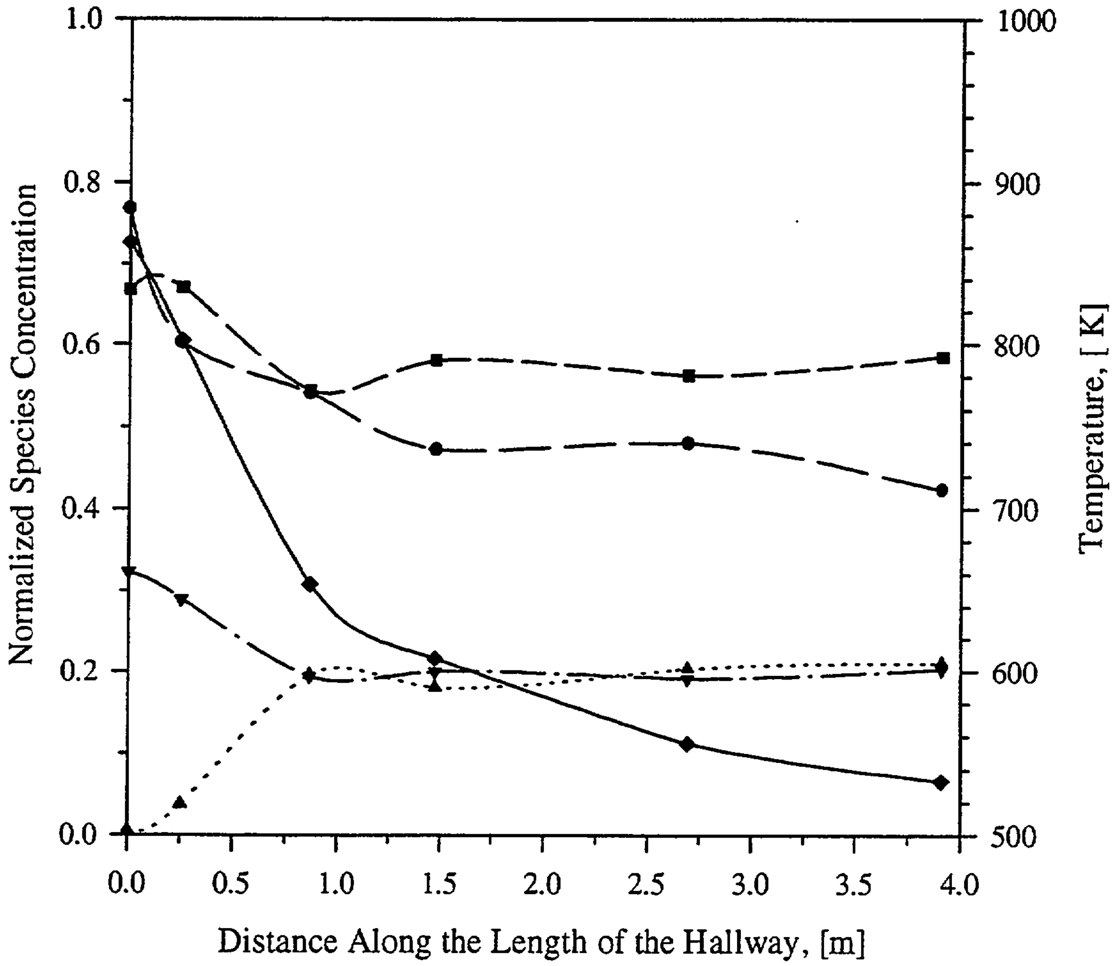


Figure 6. The variation of the species concentrations and temperatures along the length of the hallway with a door connecting the hallway and compartment. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.

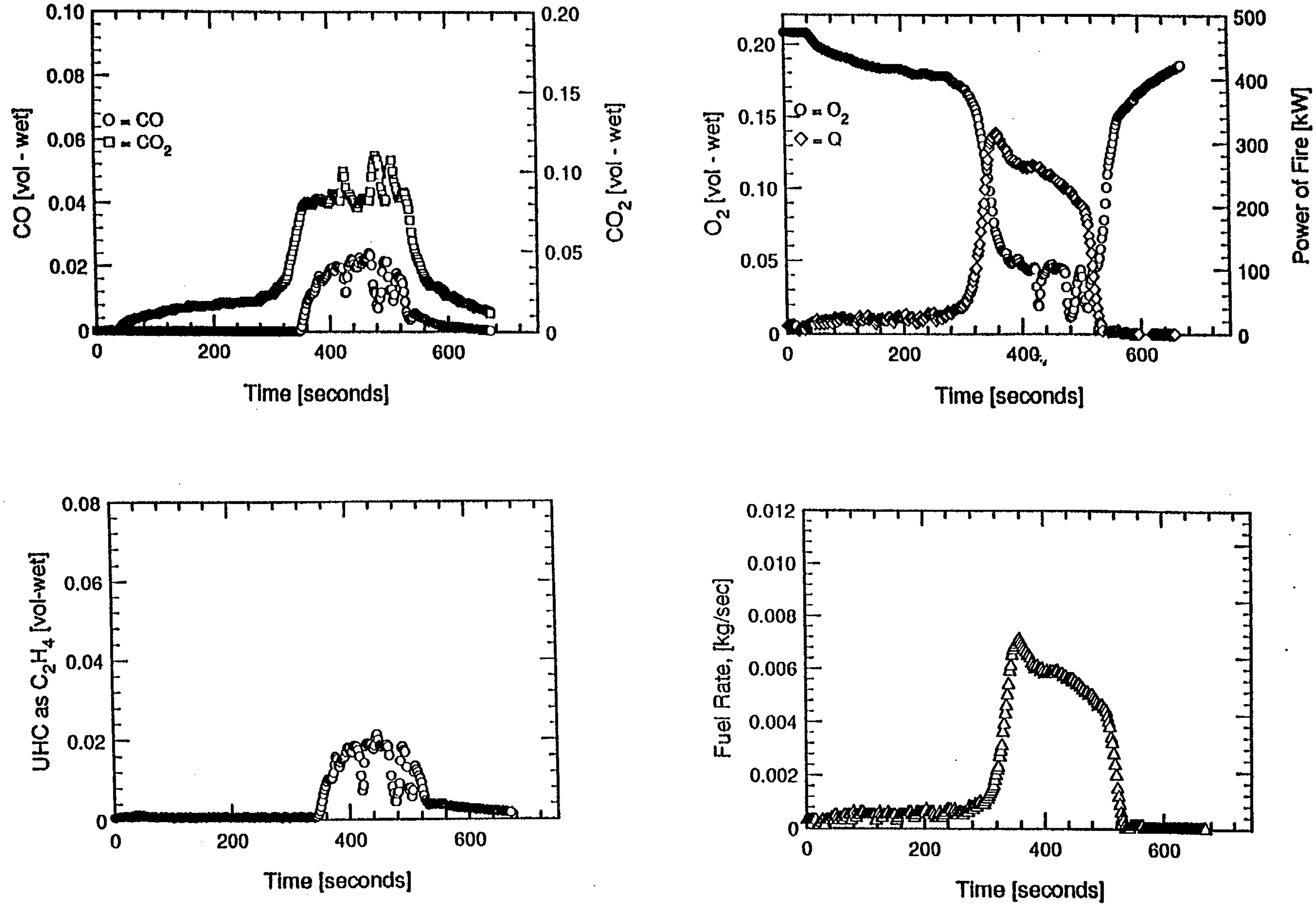


Figure 7. Temporal plots of species concentrations and the fuel burn rate at 1.32m down the hallway, 0.05 m below the ceiling.

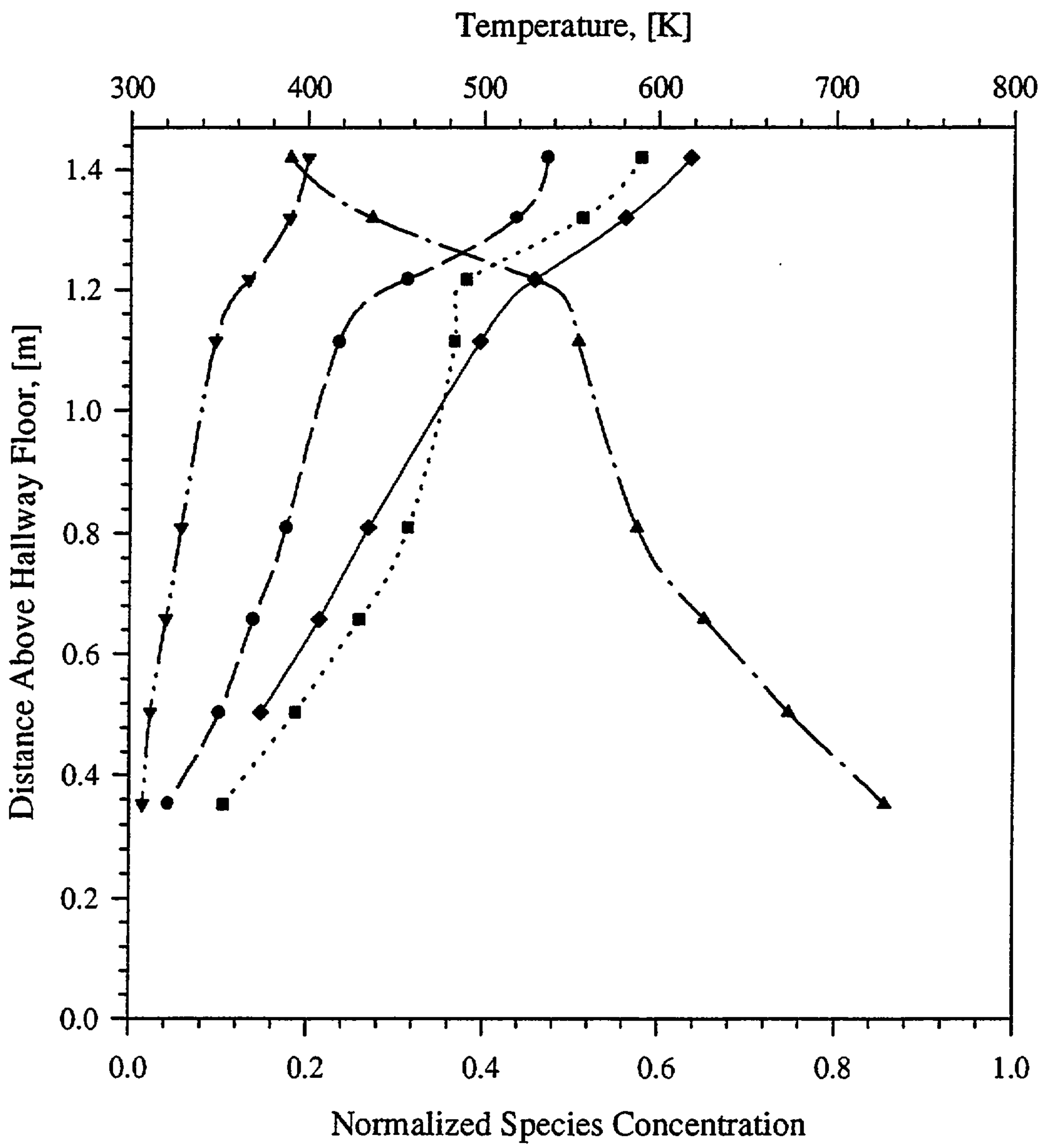


Figure 8. The variation in the species concentrations and temperatures along the height of the hallway 1.32 m down the hallway from the door at sample location L. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.

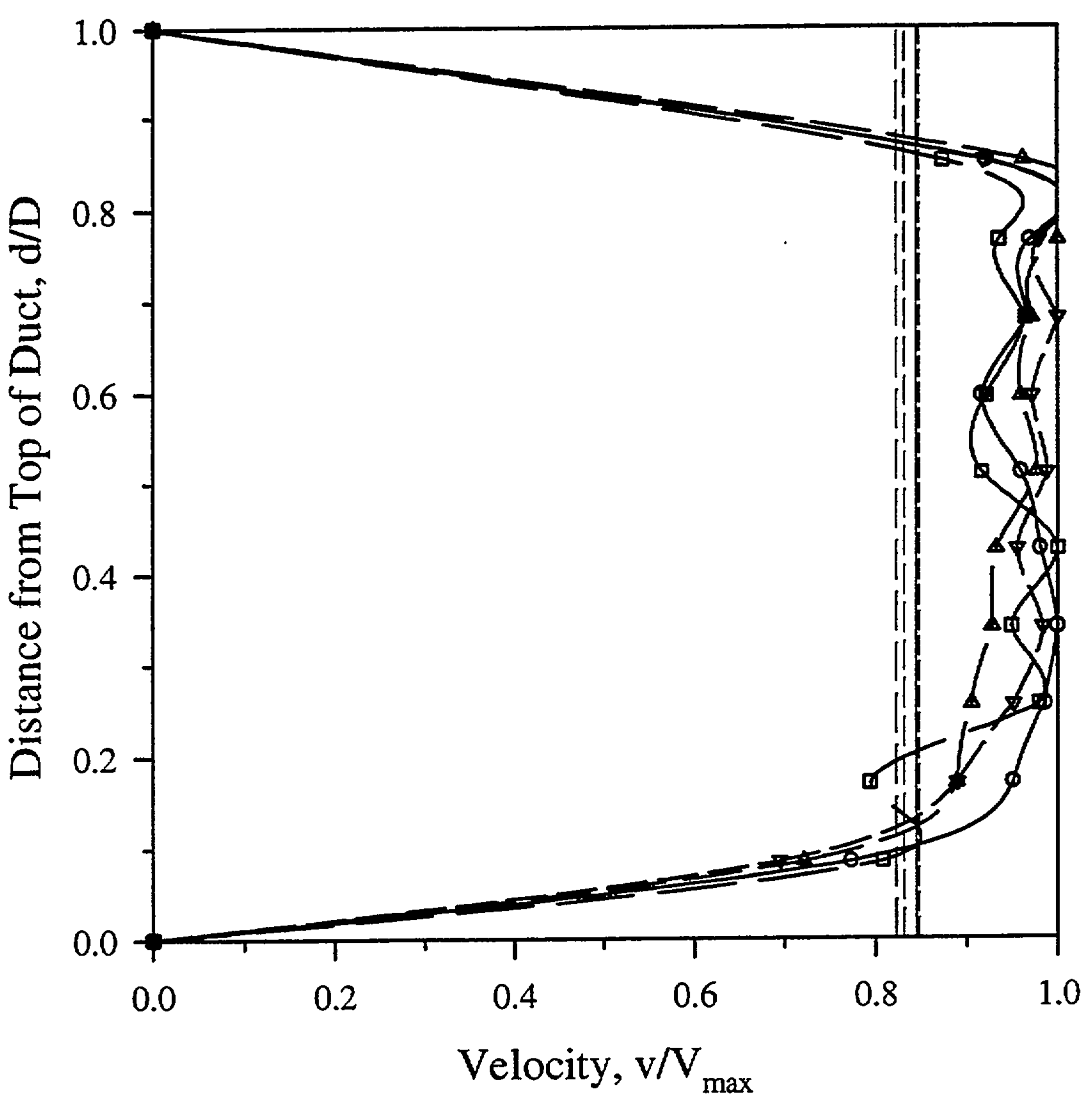


Figure 9. The velocity profiles in the air inlet duct (D=0.30m) with different diameter orifices attached: ●-no orifice, ■-0.25 m orifice, ▲-0.20 m orifice and ▼-0.15 m orifice.

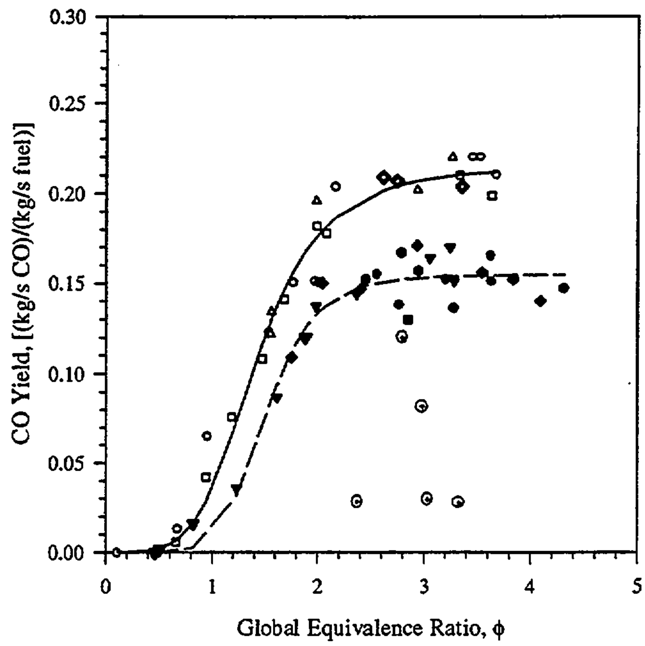


Figure 10. The CO yield plotted versus the GER. Open symbols-no external burning and closed symbols-external burning.

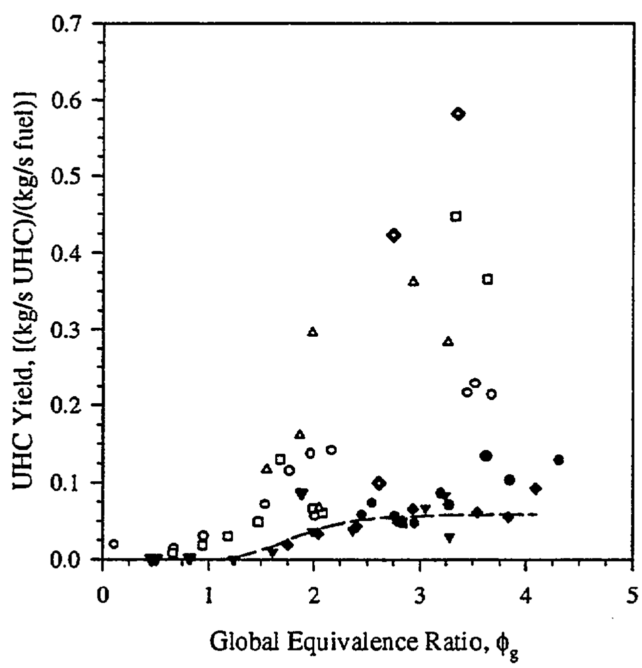


Figure 11. The UHC yield plotted versus the GER Open symbols-no external burning and closed symbols-external burning.

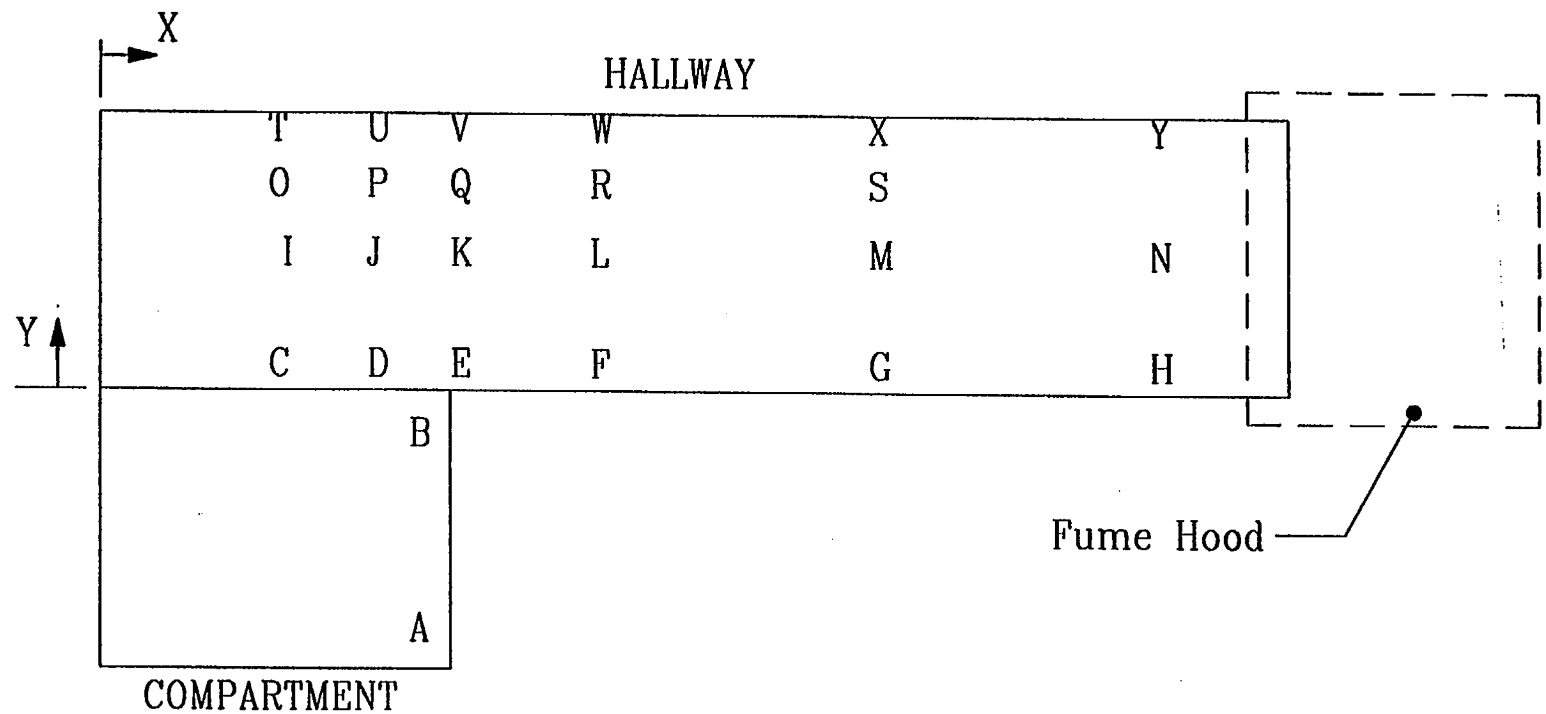


Figure 12. Possible sampling locations for hallway experiments with a window and limited air entrainment into the hallway.

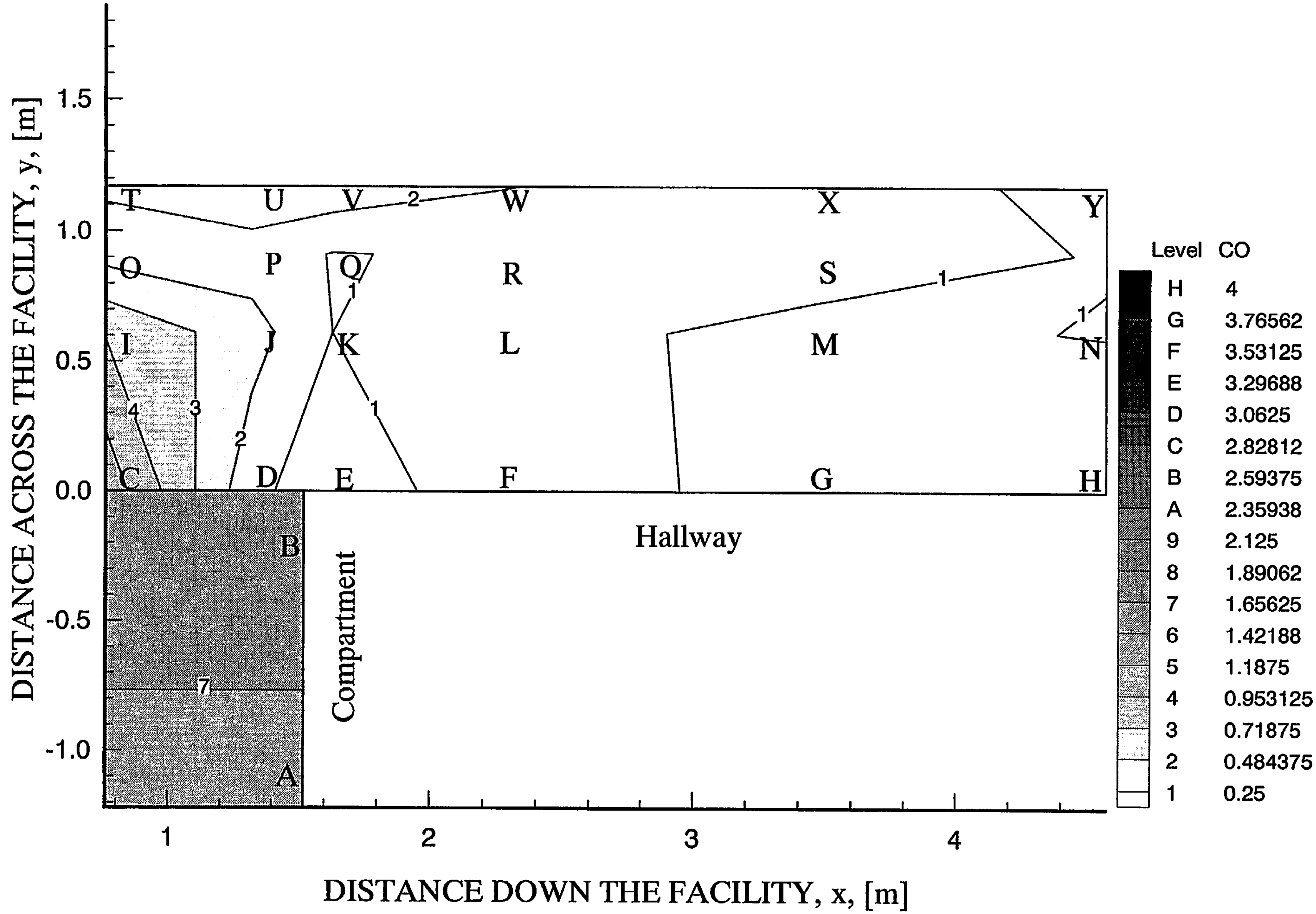


Figure 13. The CO concentration 0.05 m below the ceiling during the 10-20 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

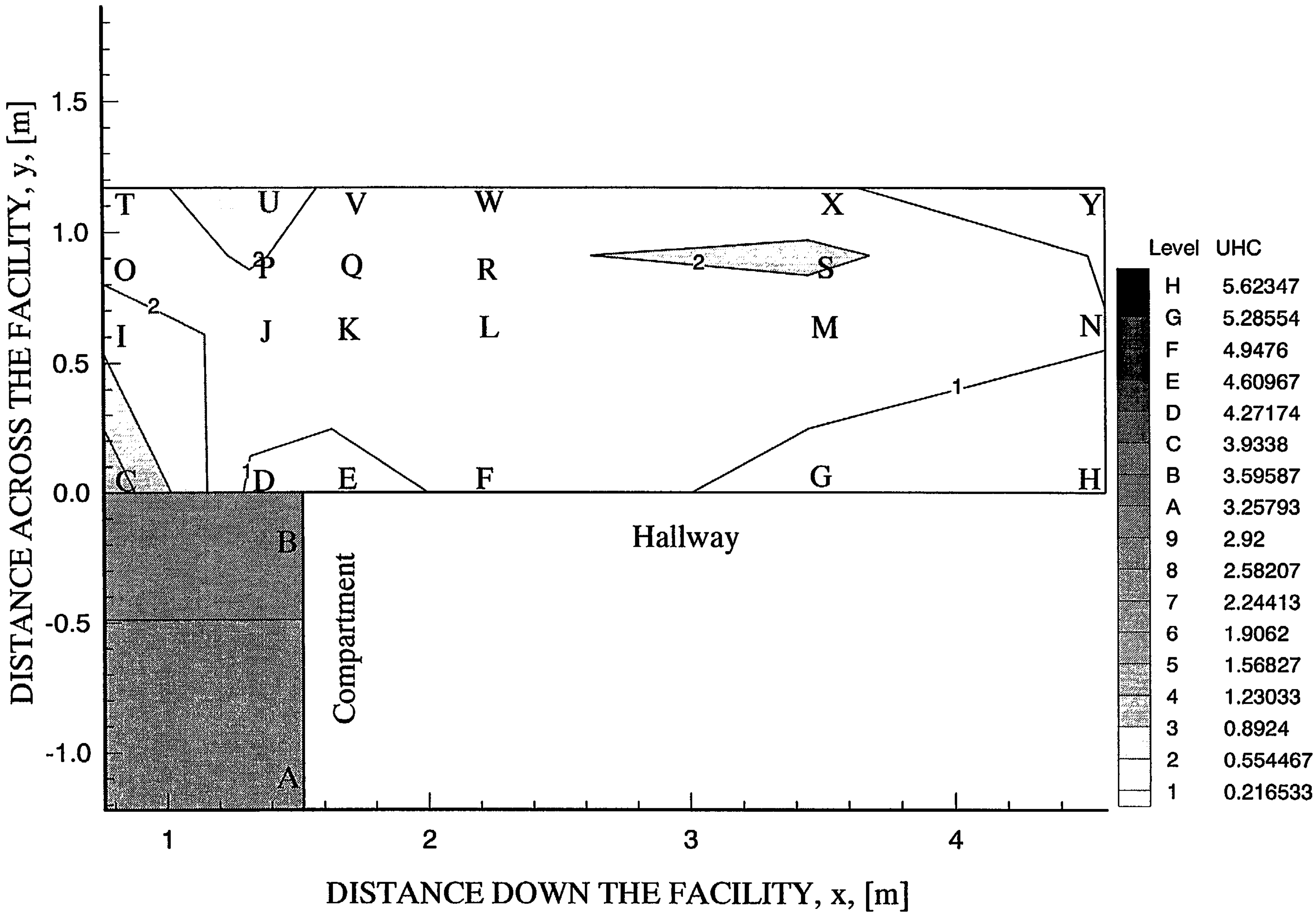


Figure 14. The UHC concentration 0.05 m below the ceiling during the 10-20 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

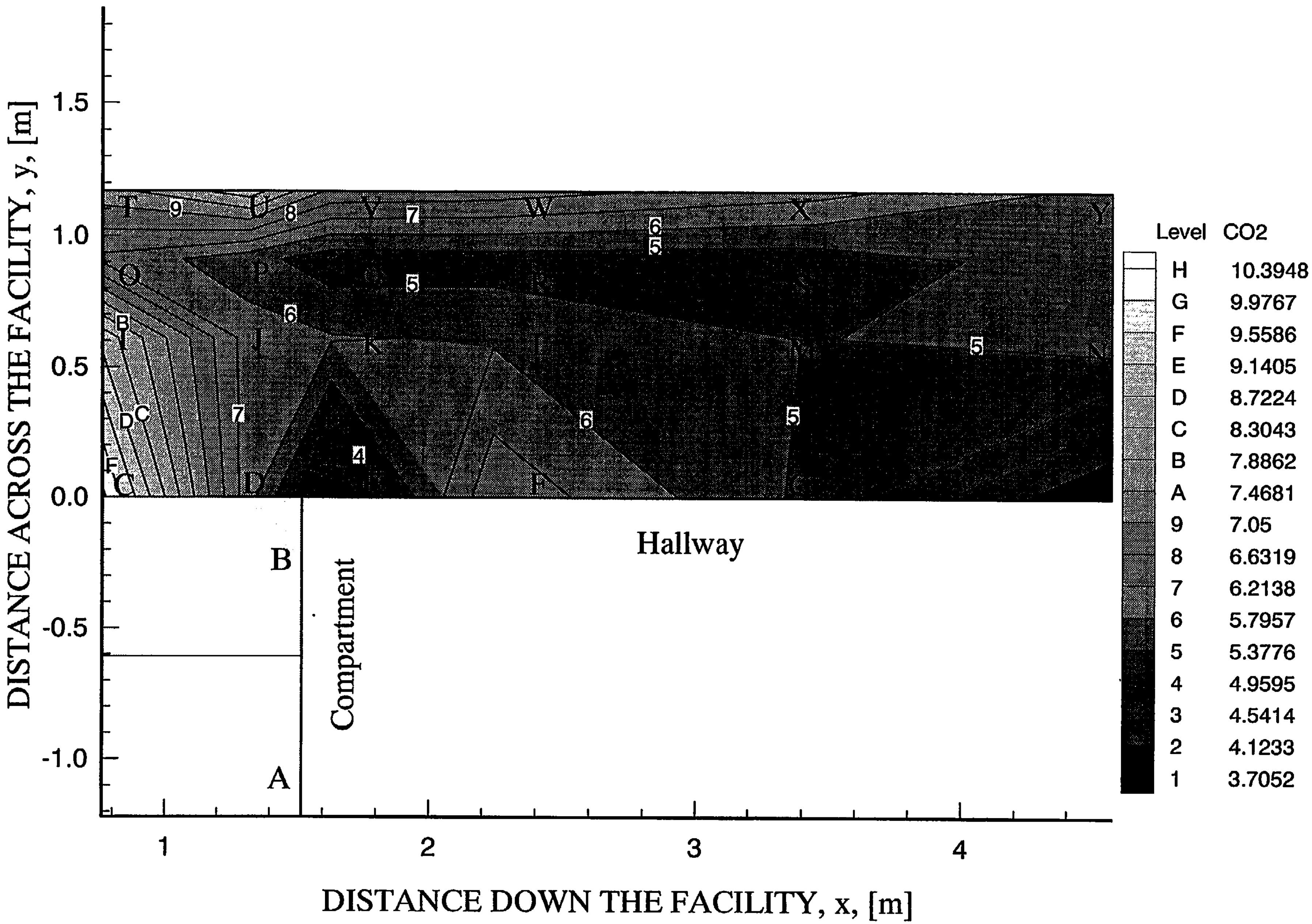


Figure 15. The CO_2 concentration 0.05 m below the ceiling during the 10-20 second interval after flashover with a 0.04 m^2 window and a 0.20 m soffit at the window.

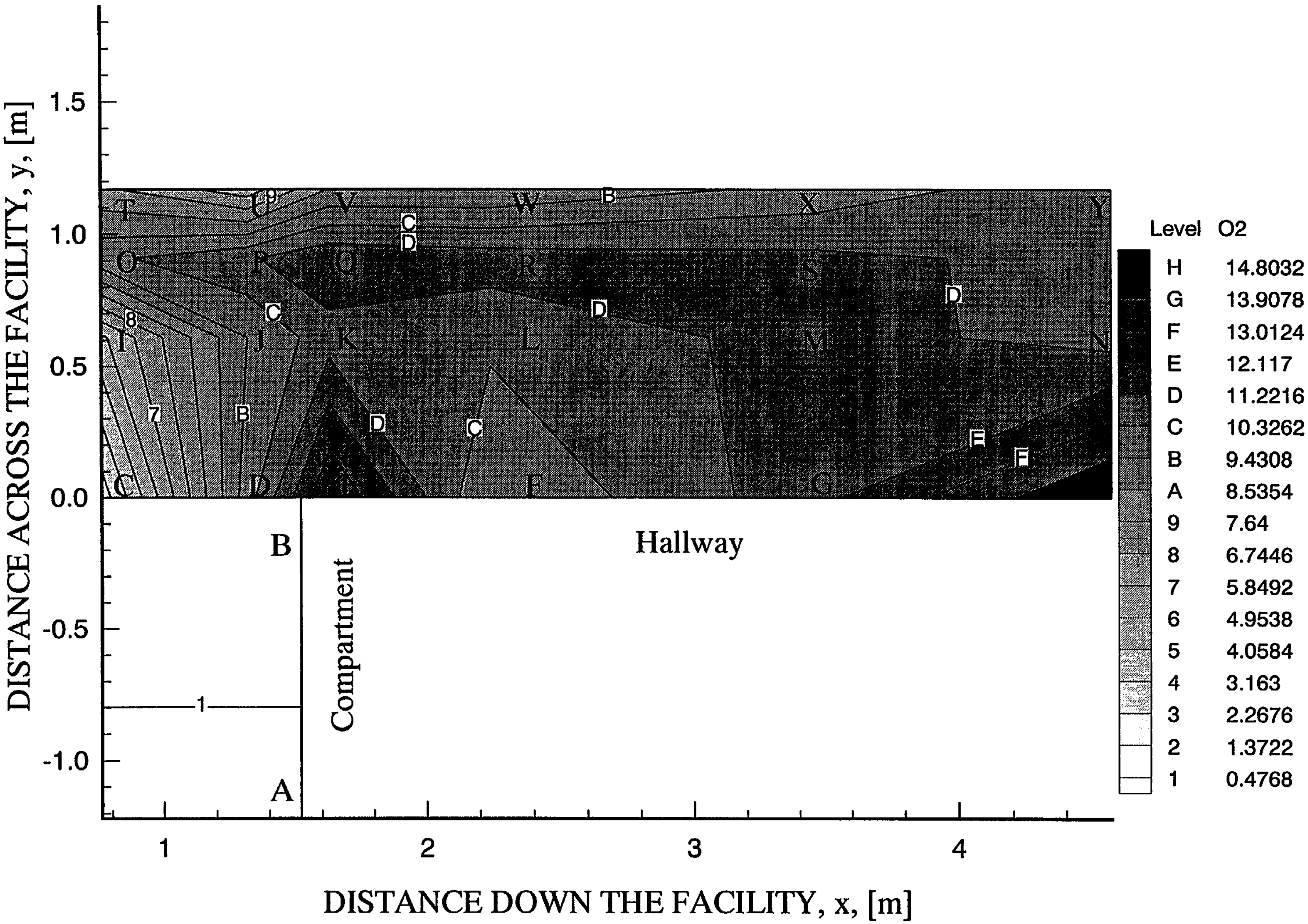


Figure 16. The O_2 concentration 0.05 m below the ceiling during the 10-20 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

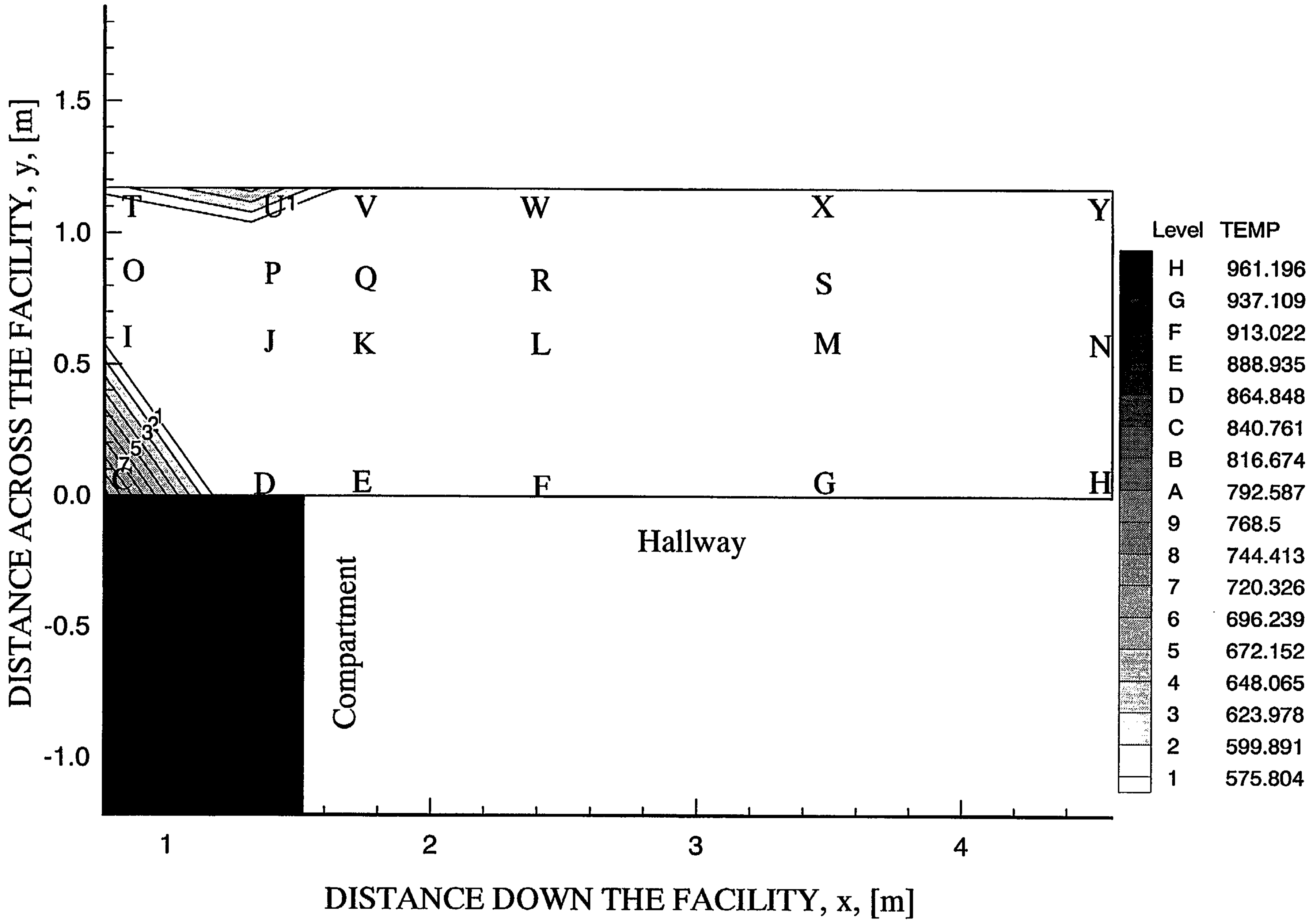


Figure 17. The temperature 0.05 m below the ceiling during 10-20 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

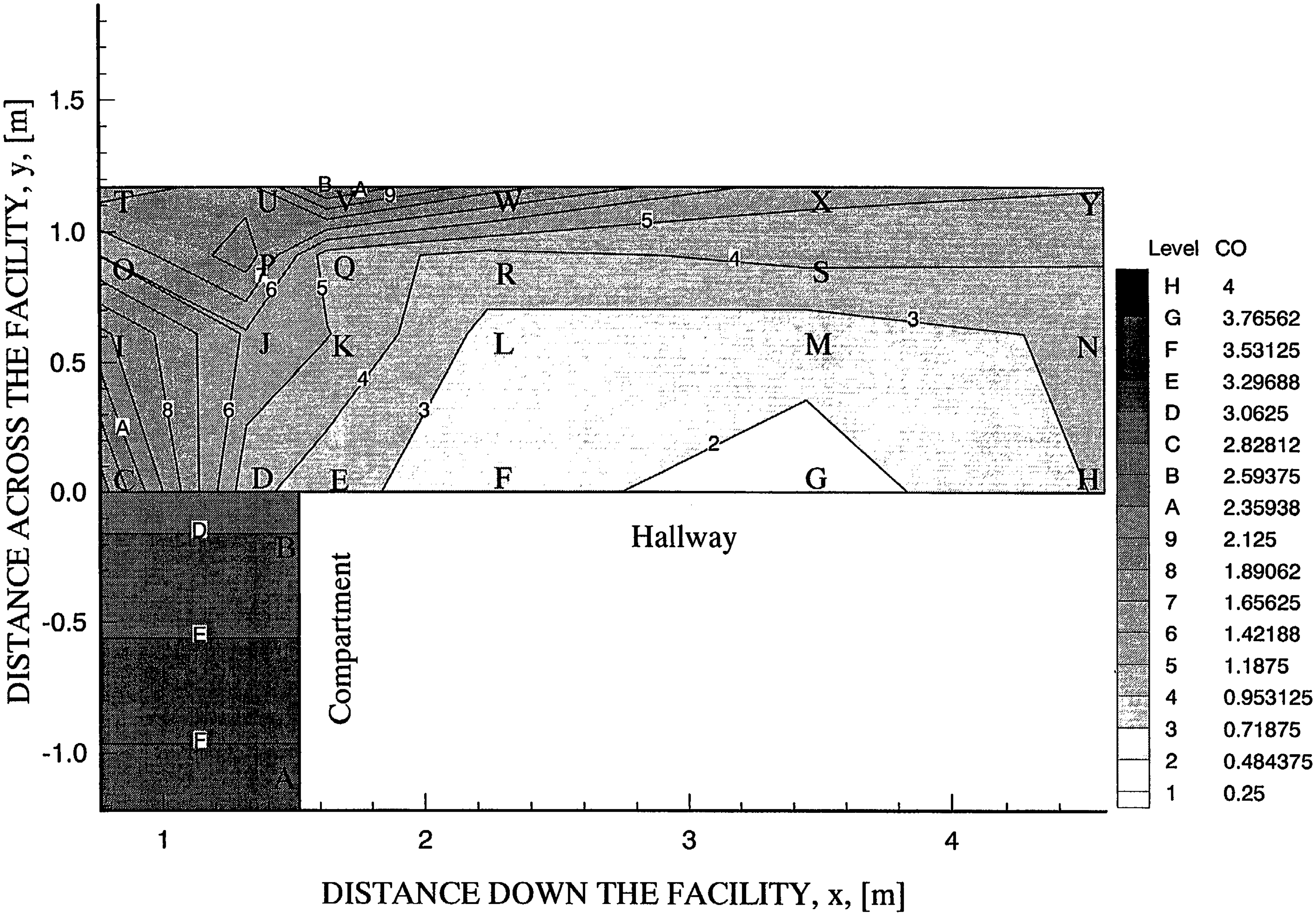


Figure 18. The CO concentration 0.05 m below the ceiling during the 30-40 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

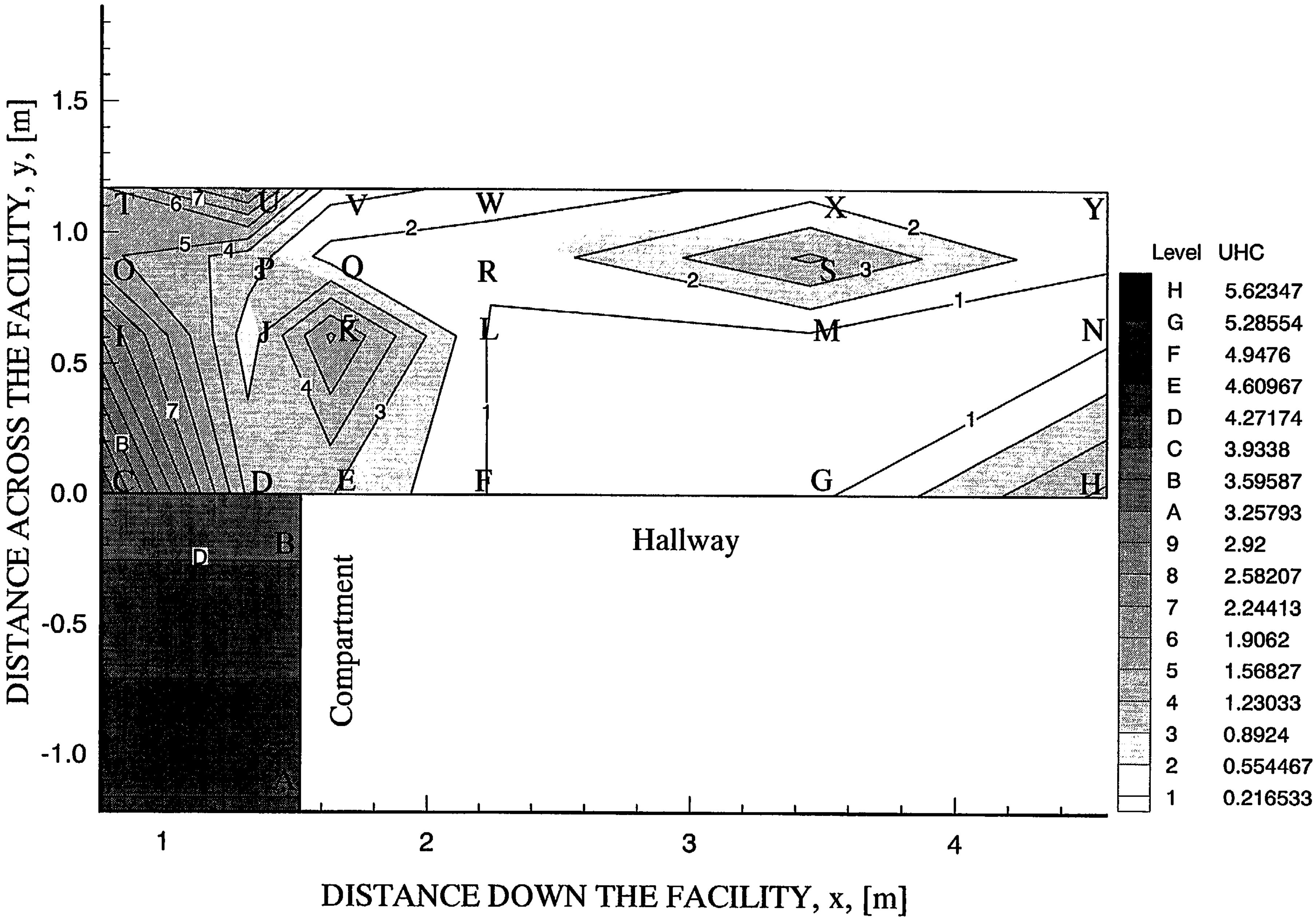


Figure 19. The UHC concentration 0.05 m below the ceiling during the 30-40 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

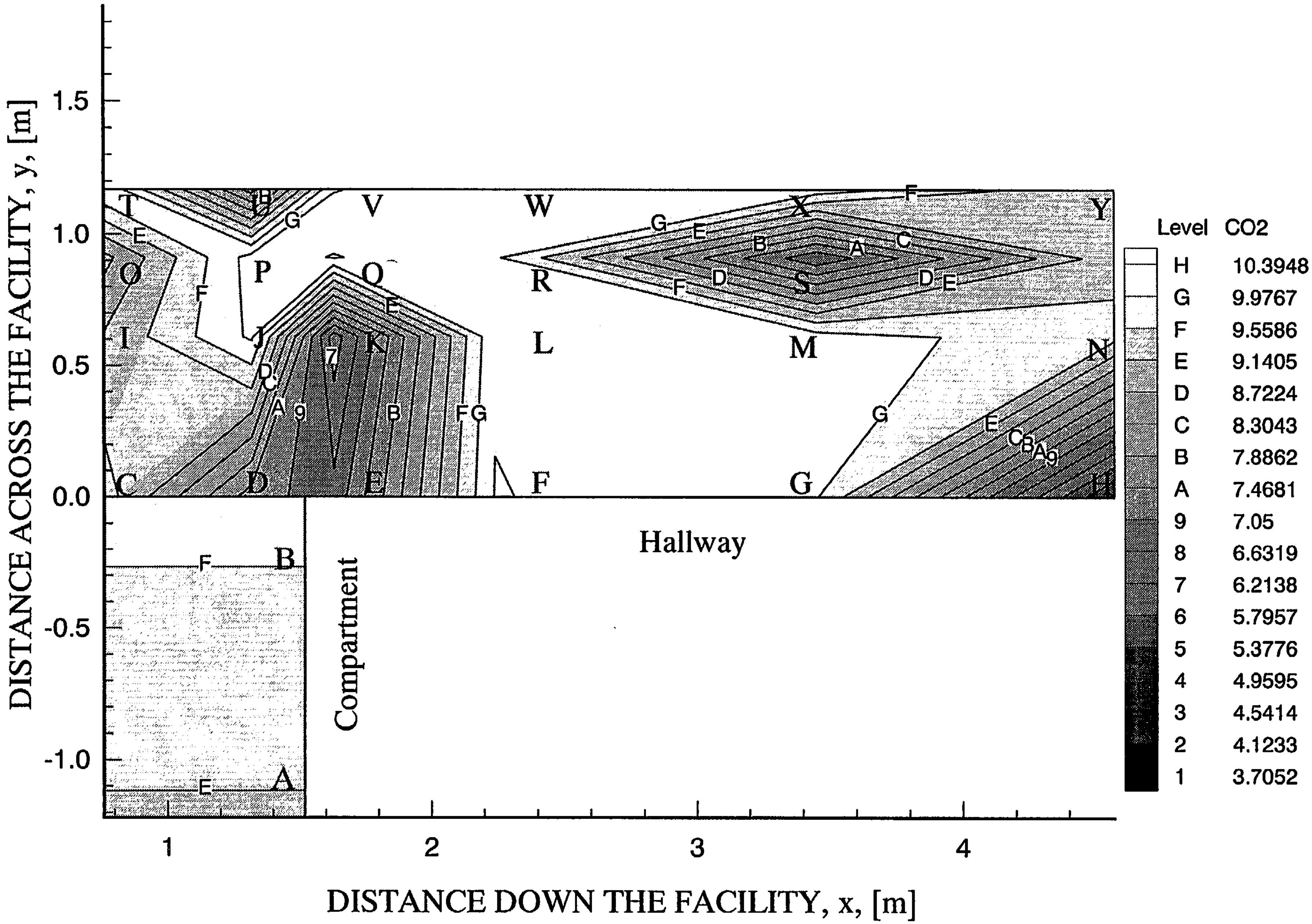


Figure 20. The CO_2 concentration 0.05 m below the ceiling during the 30-40 second interval after flashover with a 0.04 m^2 window and a 0.20 m soffit at the window.

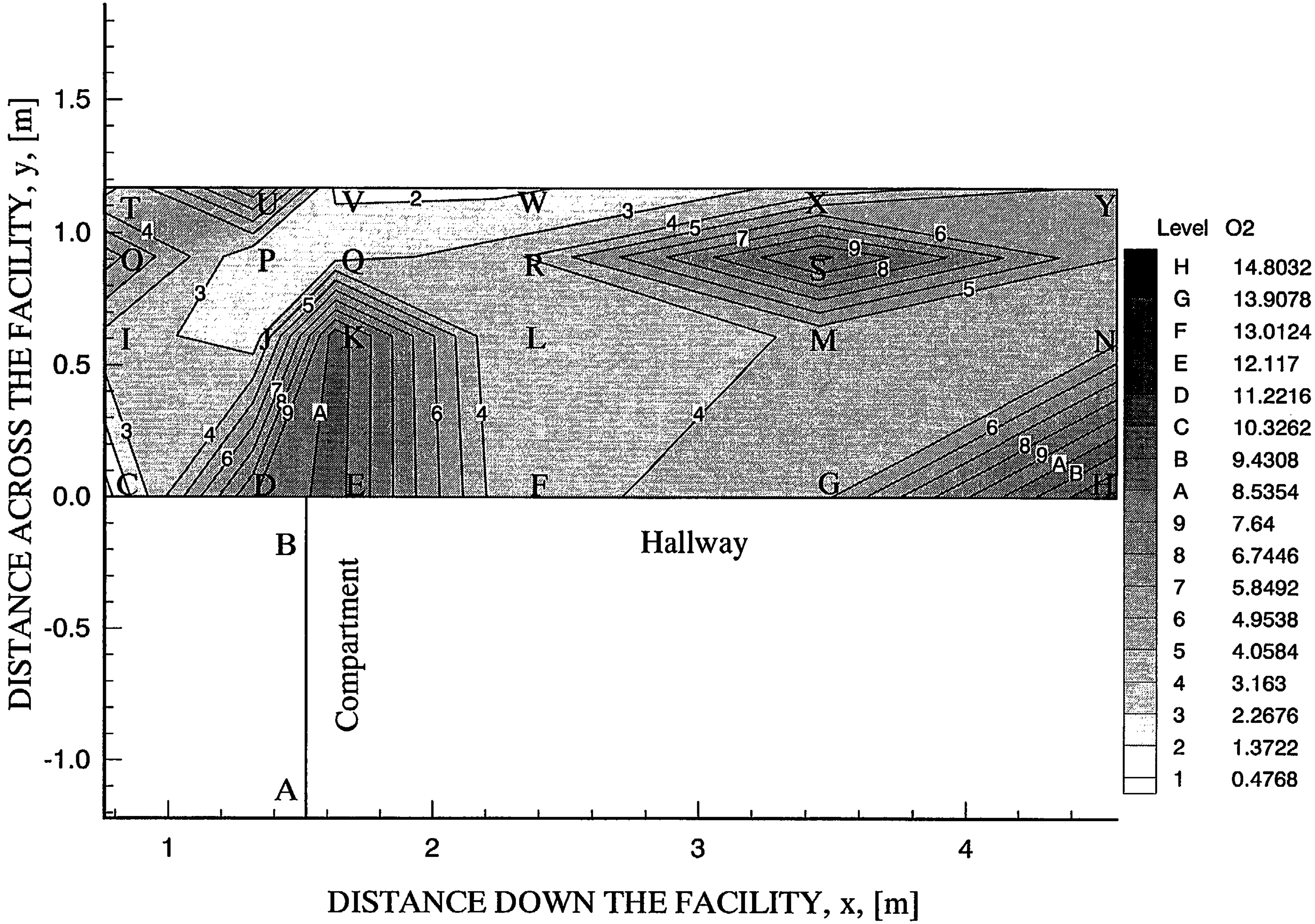


Figure 21. The O_2 concentration 0.05 m below the ceiling during the 30-40 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

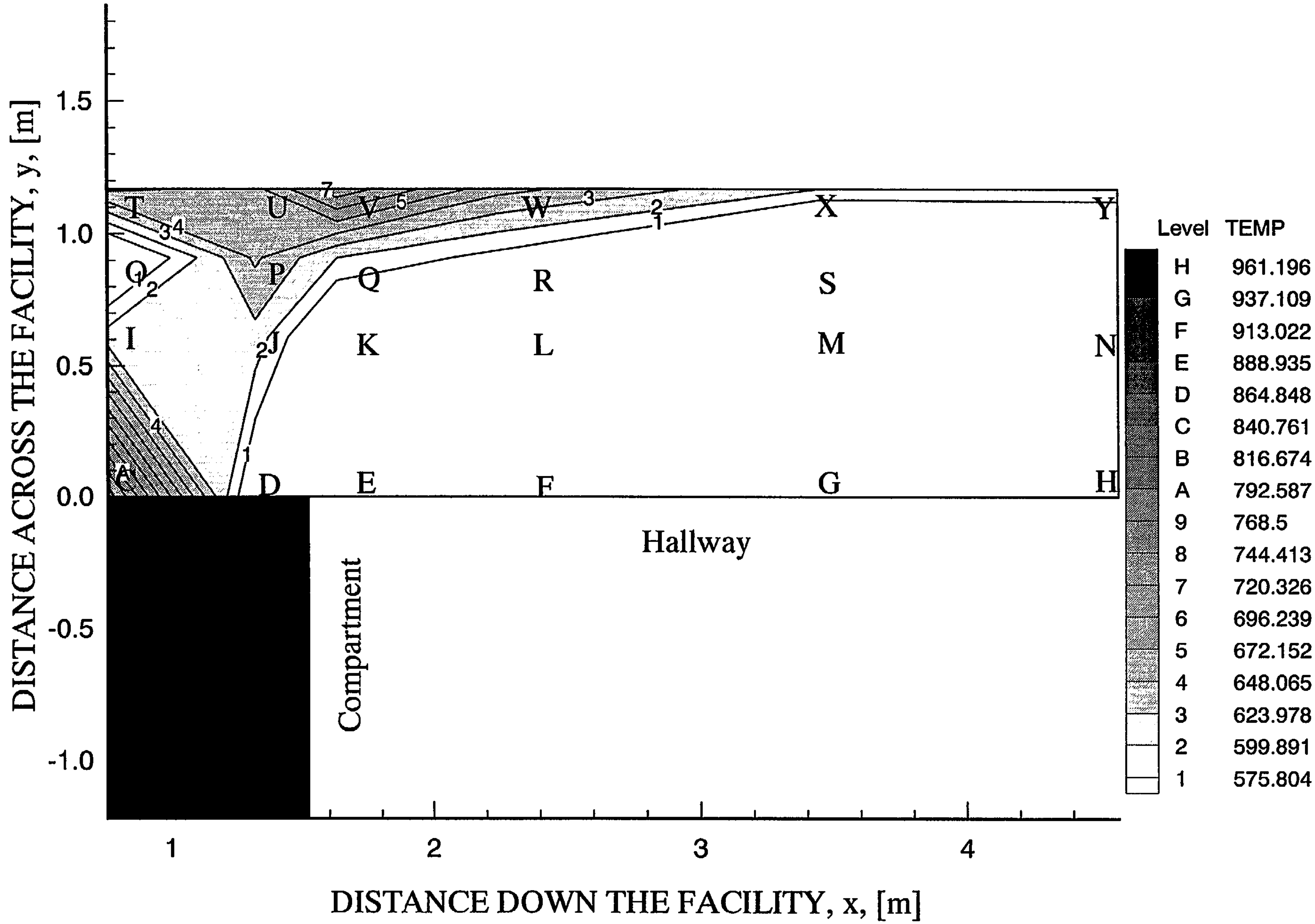


Figure 22. The temperature 0.05 m below the ceiling during 30-40 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

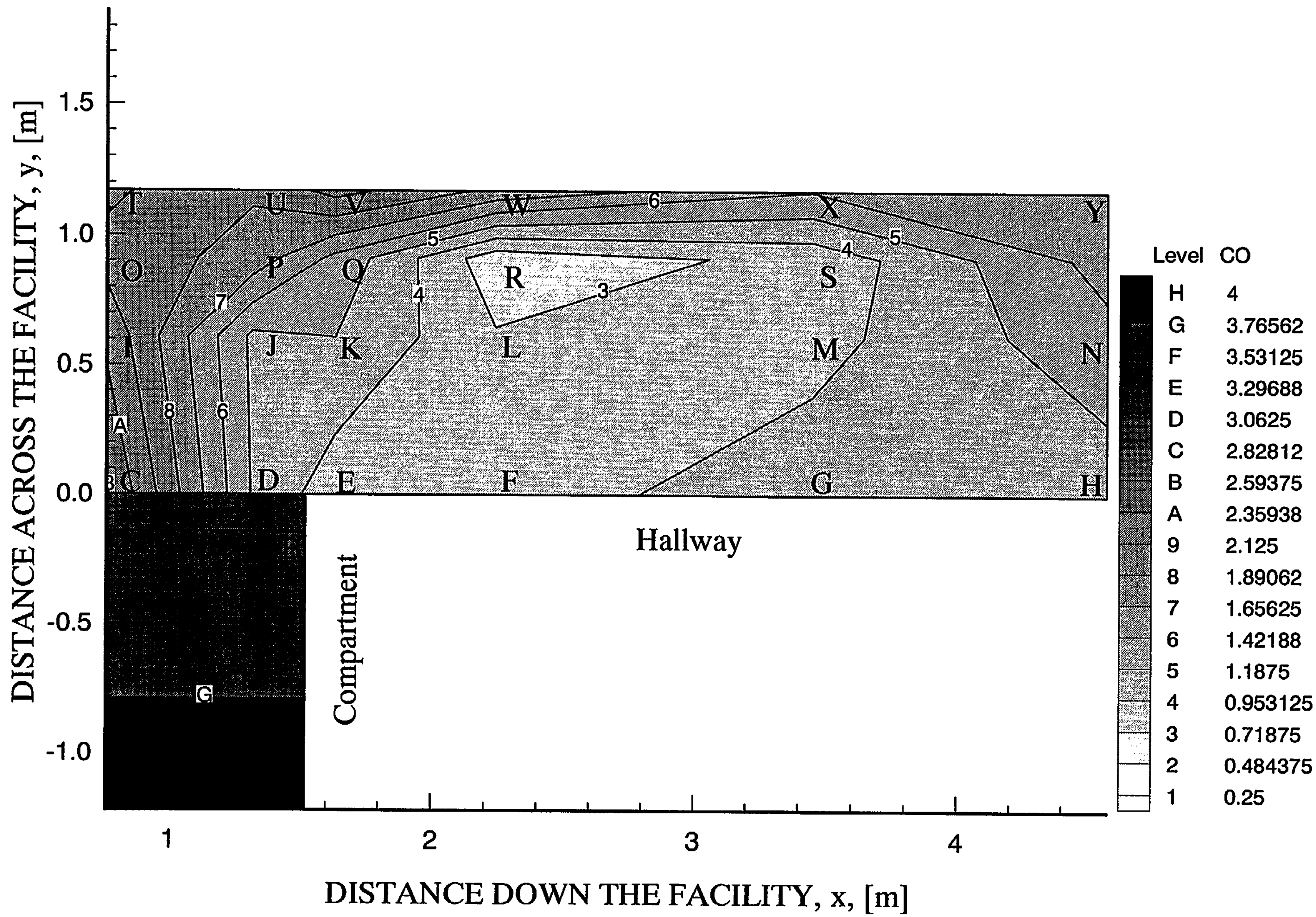


Figure 23. The CO concentration 0.05 m below the ceiling during the 50-60 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

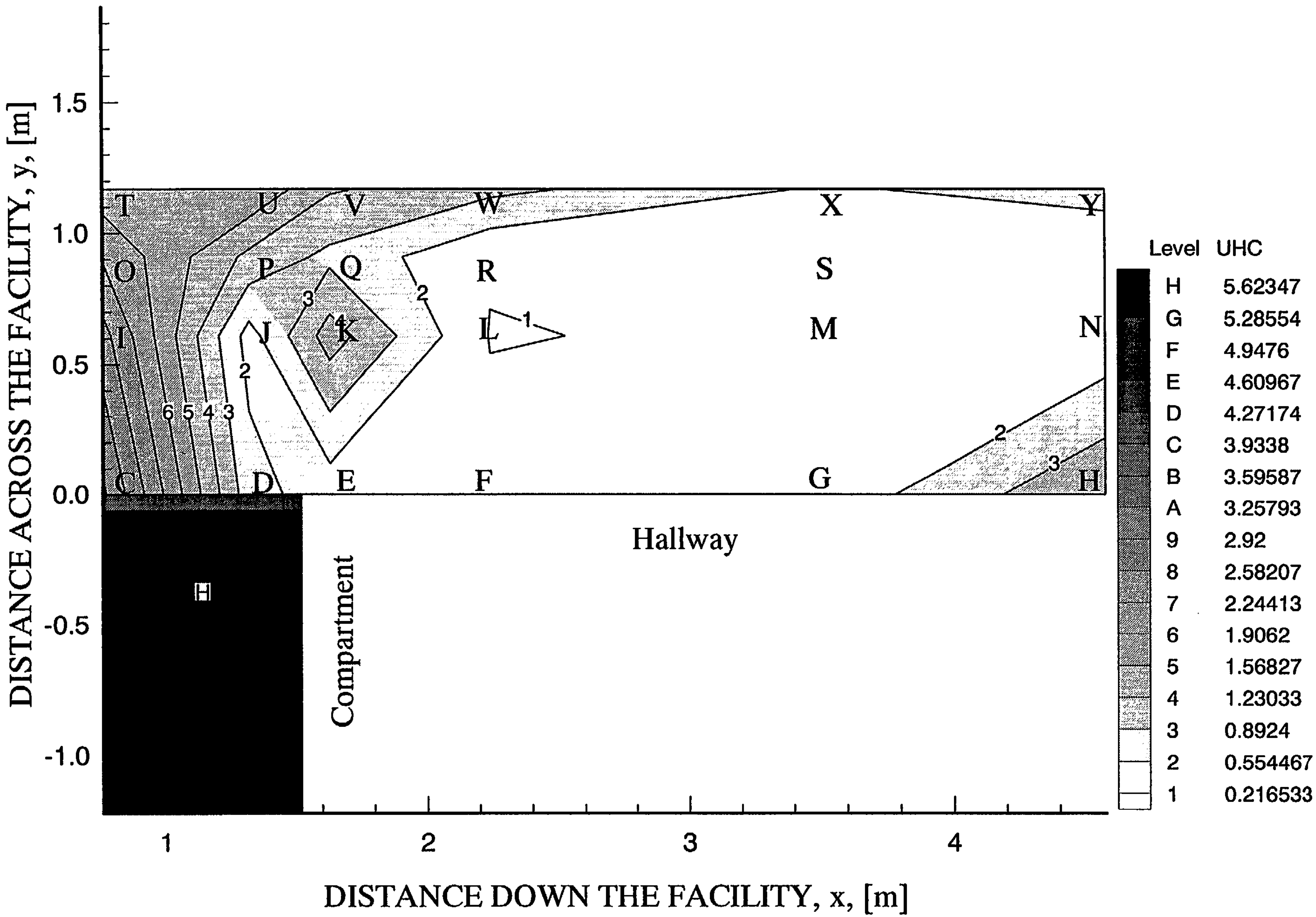


Figure 24. The UHC concentration 0.05 m below the ceiling during the 50-60 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

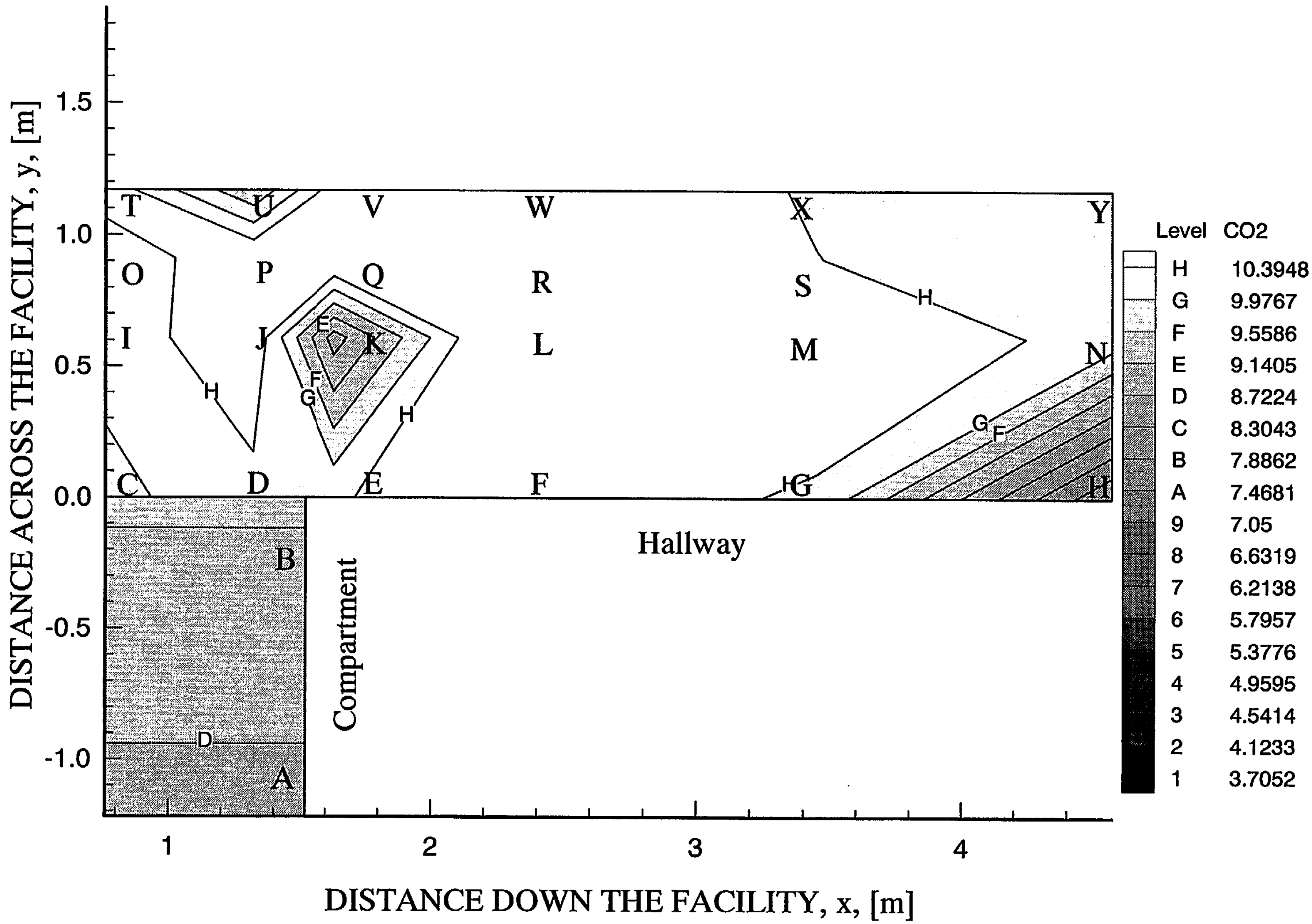


Figure 25. The CO_2 concentration 0.05 m below the ceiling during the 50-60 second interval after flashover with a 0.04 m^2 window and a 0.20 m soffit at the window.

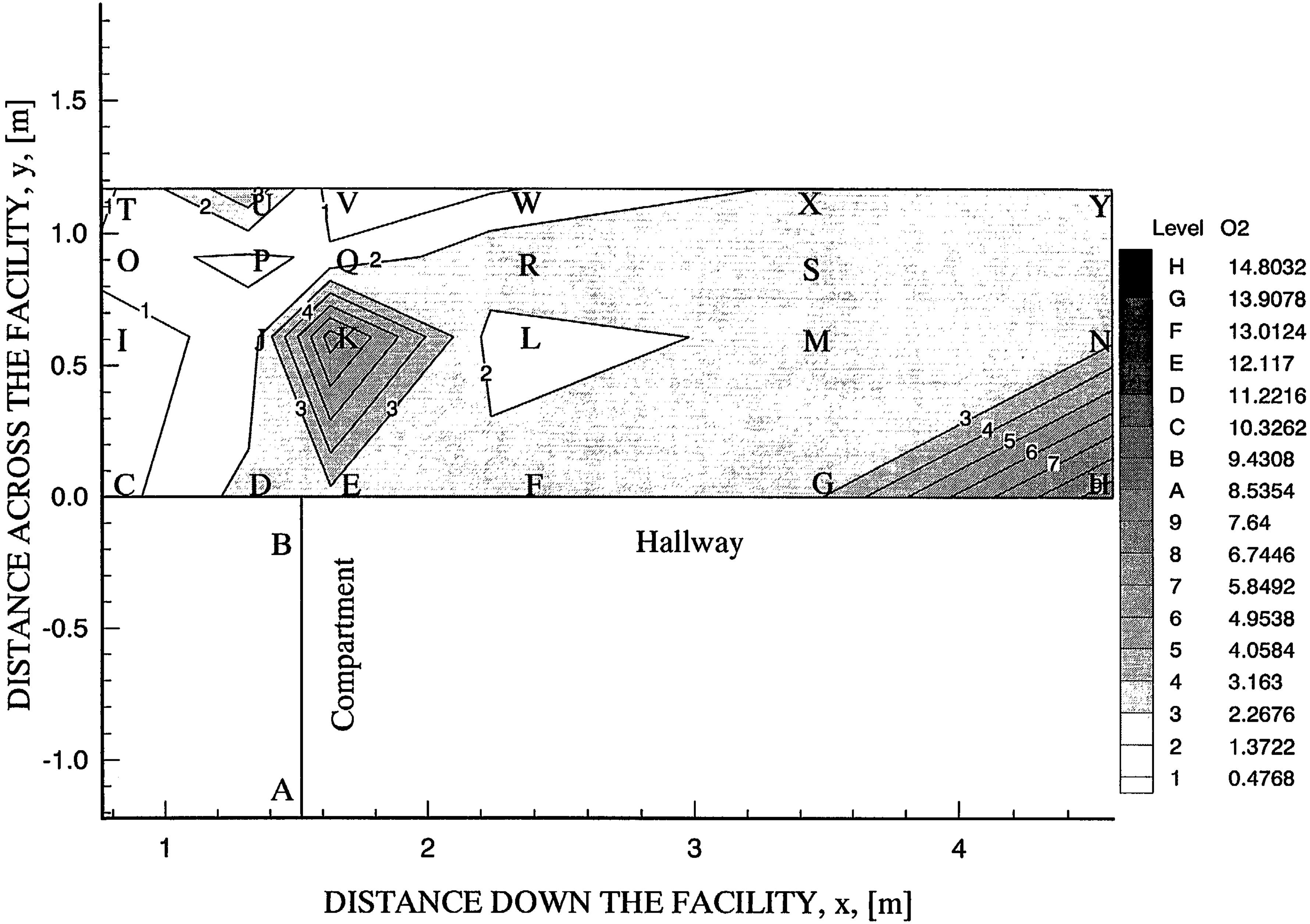


Figure 26. The O_2 concentration 0.05 m below the ceiling during the 50-60 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

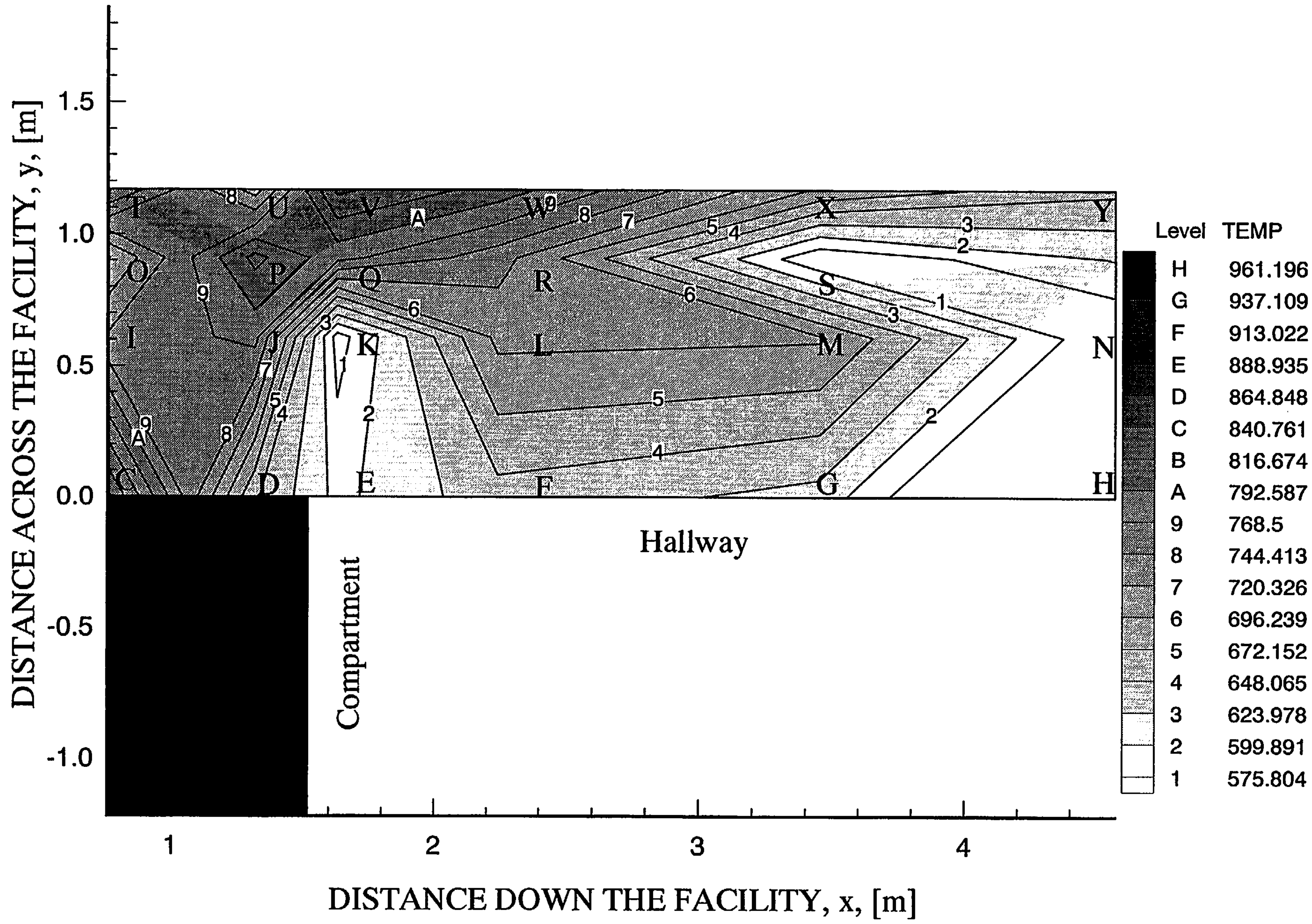


Figure 27. The temperature 0.05 m below the ceiling during 50-60 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

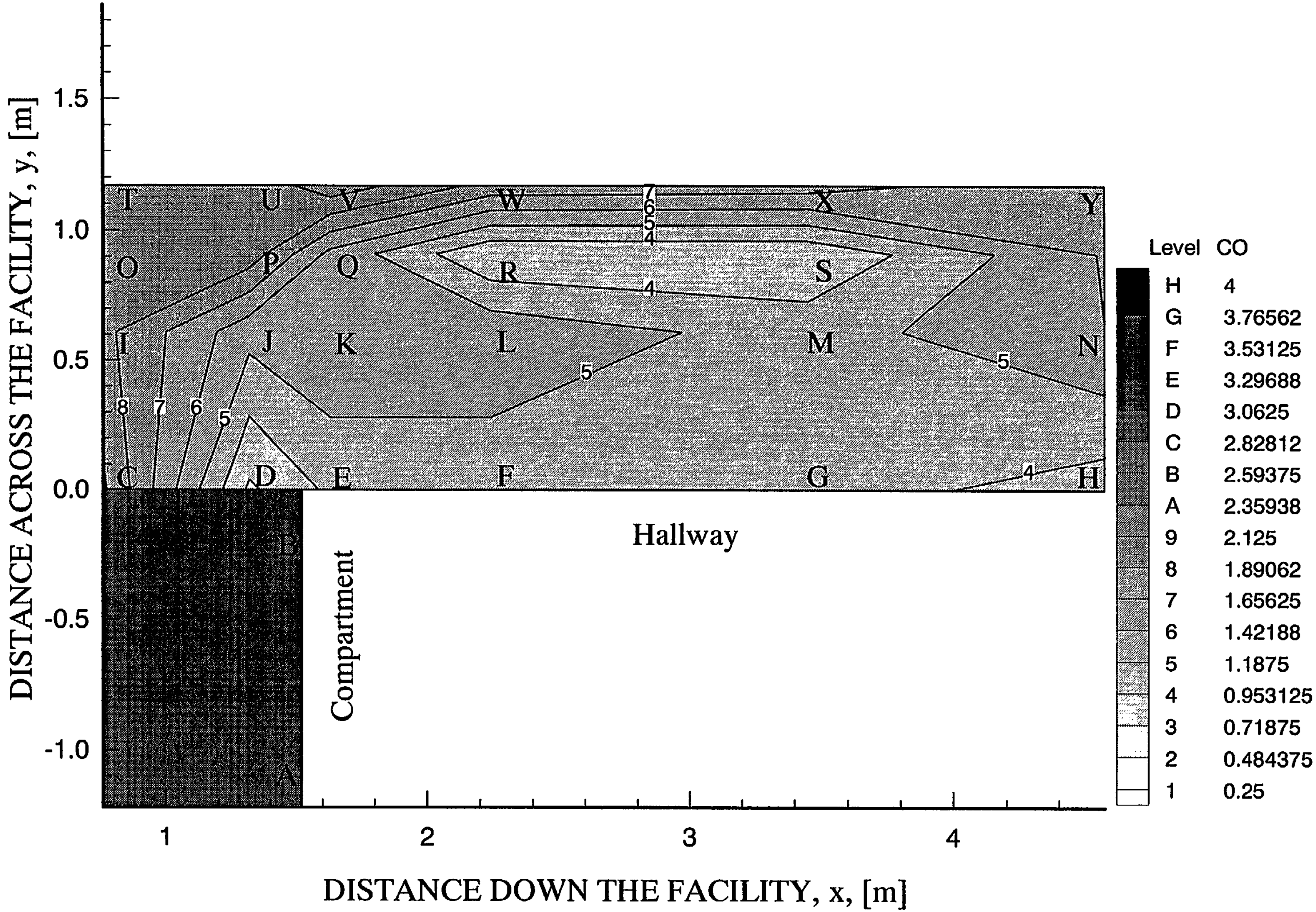


Figure 18. The CO concentration 0.05 m below the ceiling during the 70-80 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

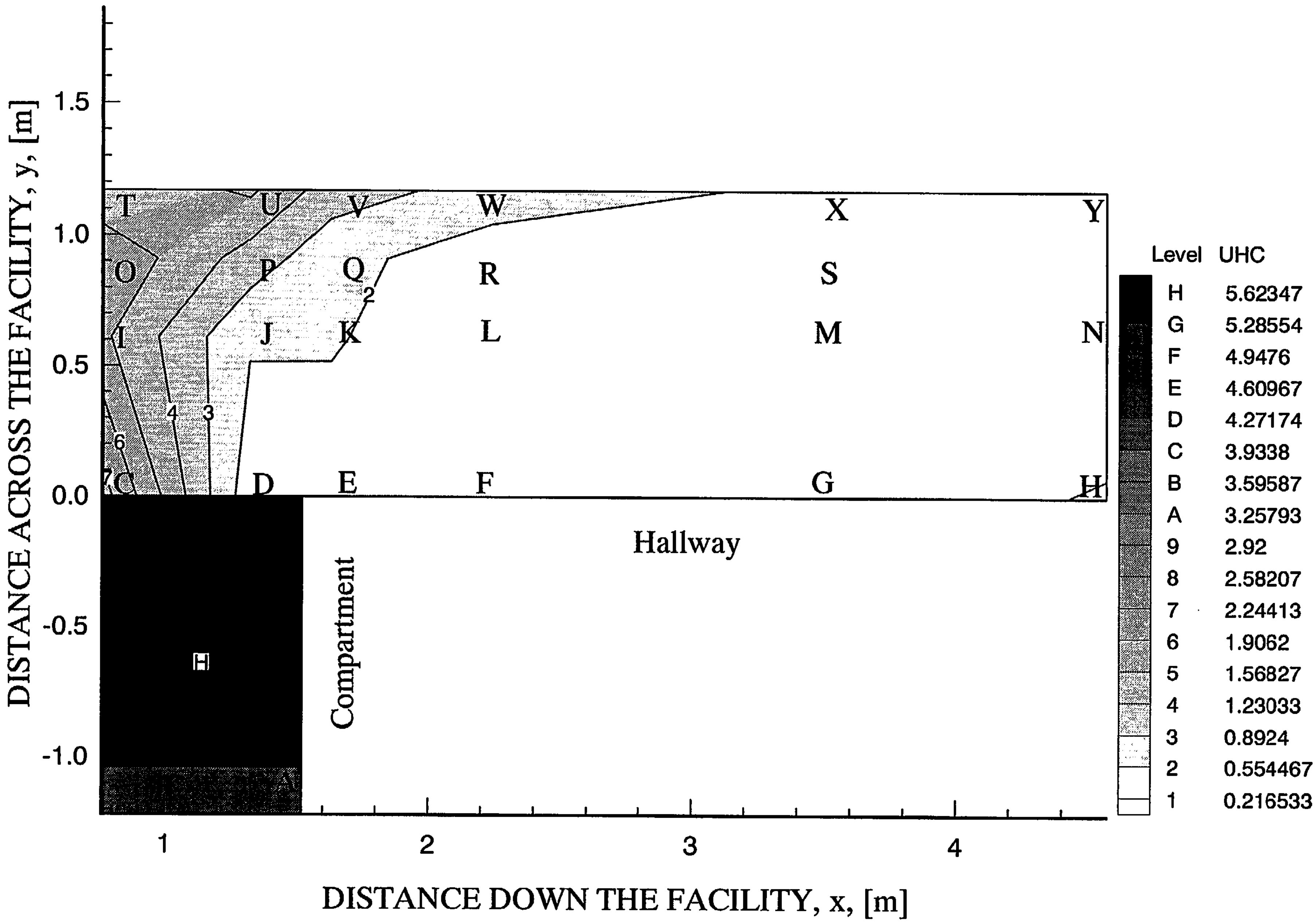


Figure 29. The UHC concentration 0.05 m below the ceiling during the 70-80 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

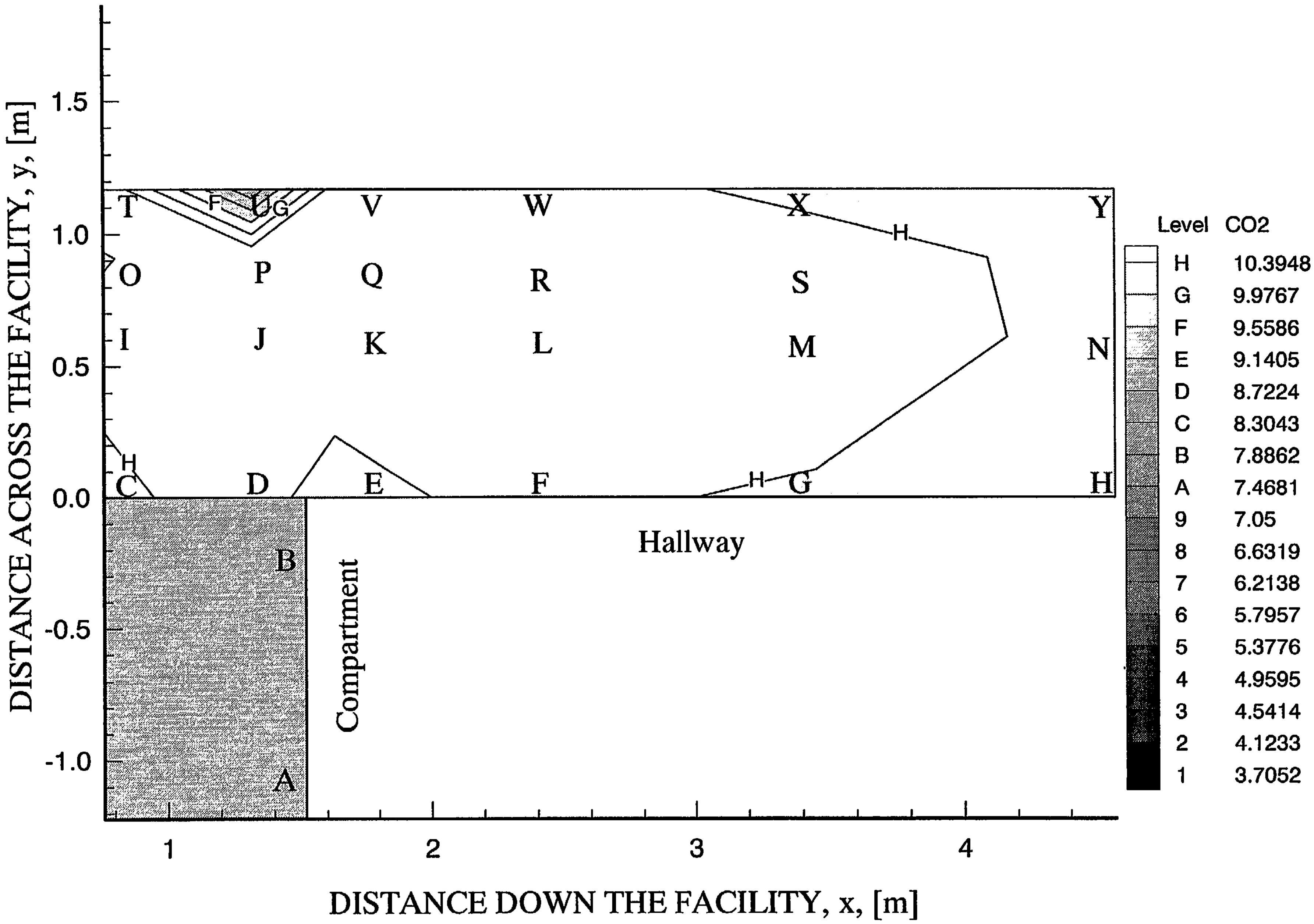


Figure 30. The CO_2 concentration 0.05 m below the ceiling during the 70-80 second interval after flashover with a 0.04 m^2 window and a 0.20 m soffit at the window.

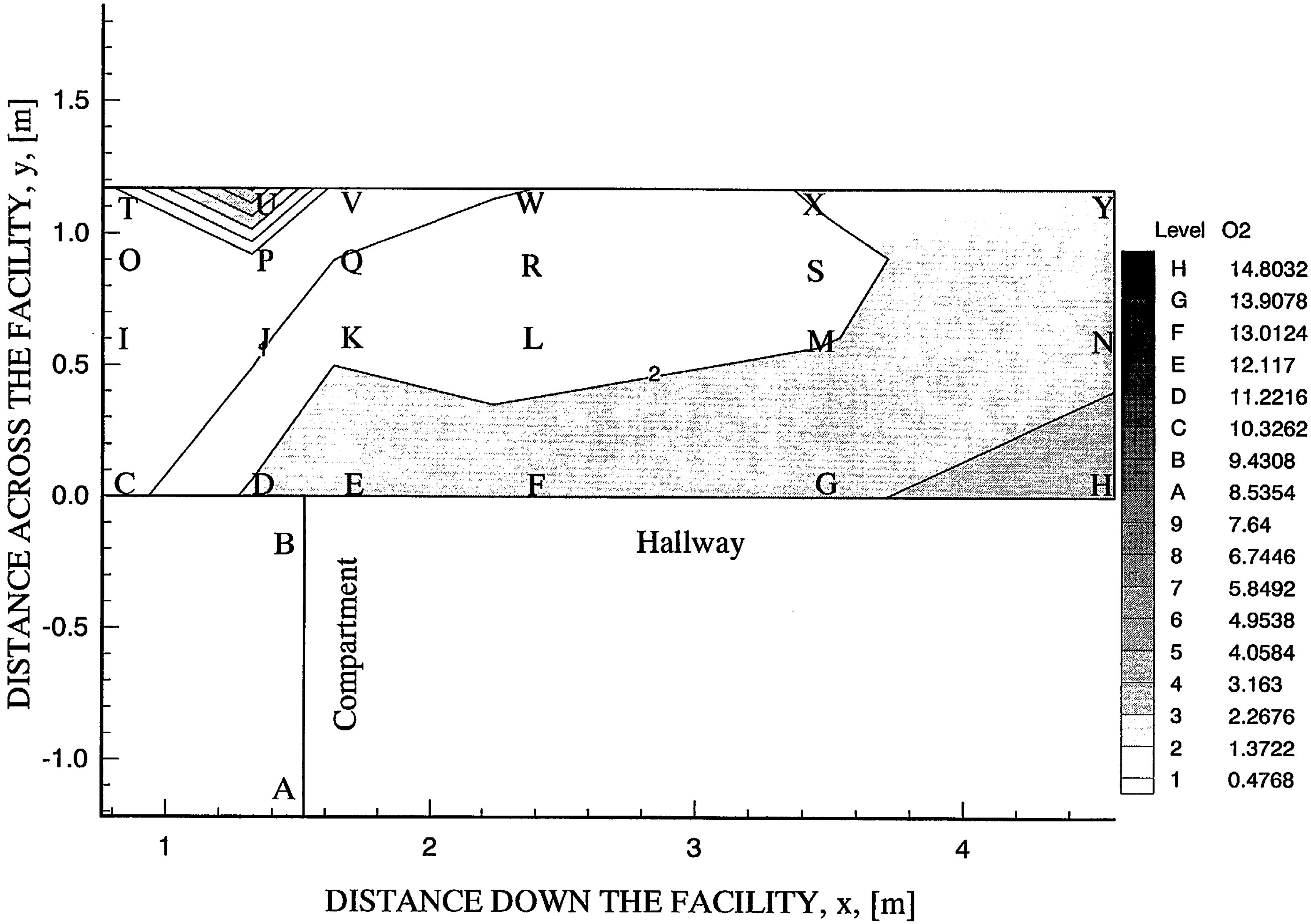


Figure 31. The O_2 concentration 0.05 m below the ceiling during the 70-80 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

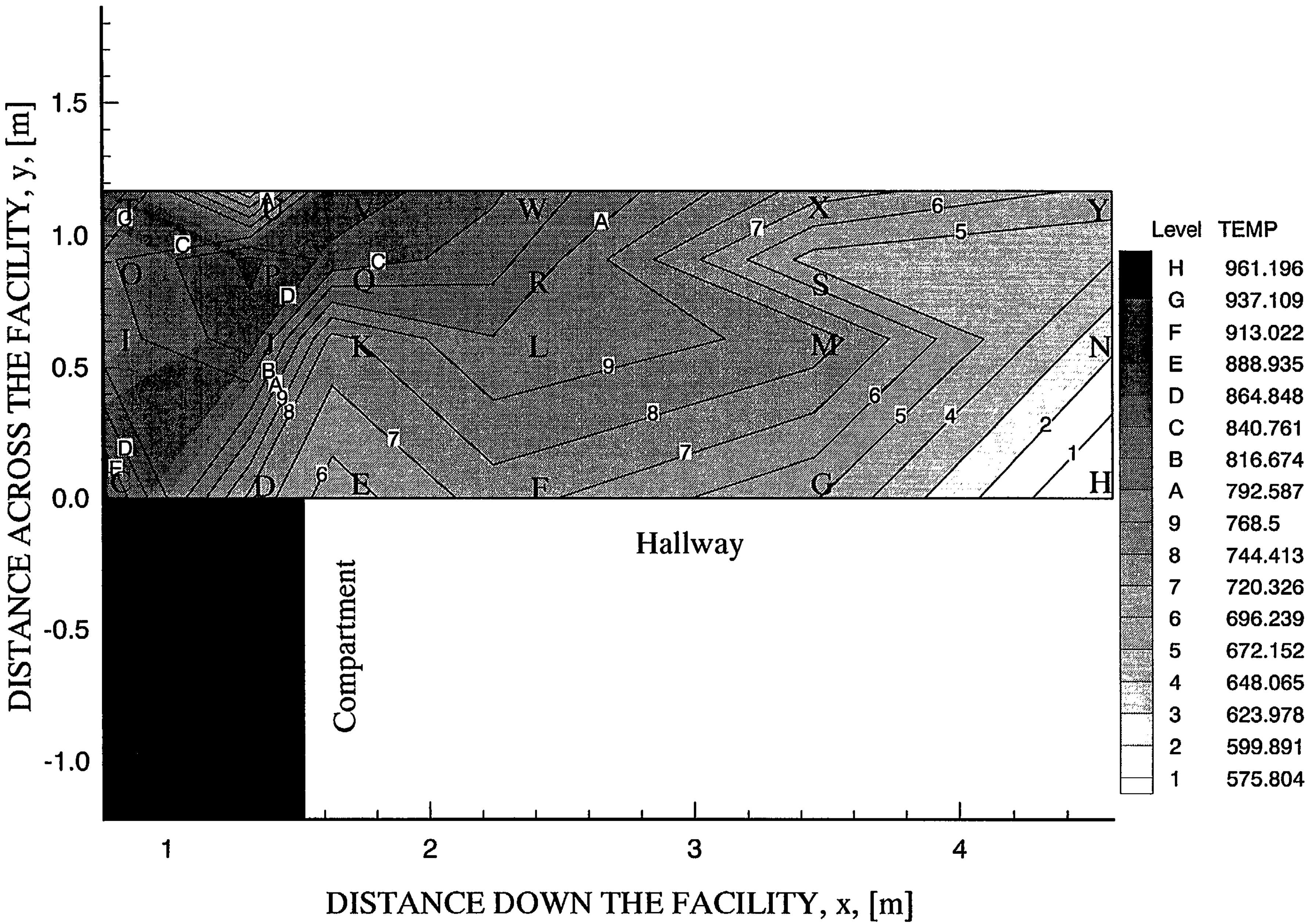


Figure 32. The temperature 0.05 m below the ceiling during 70-80 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

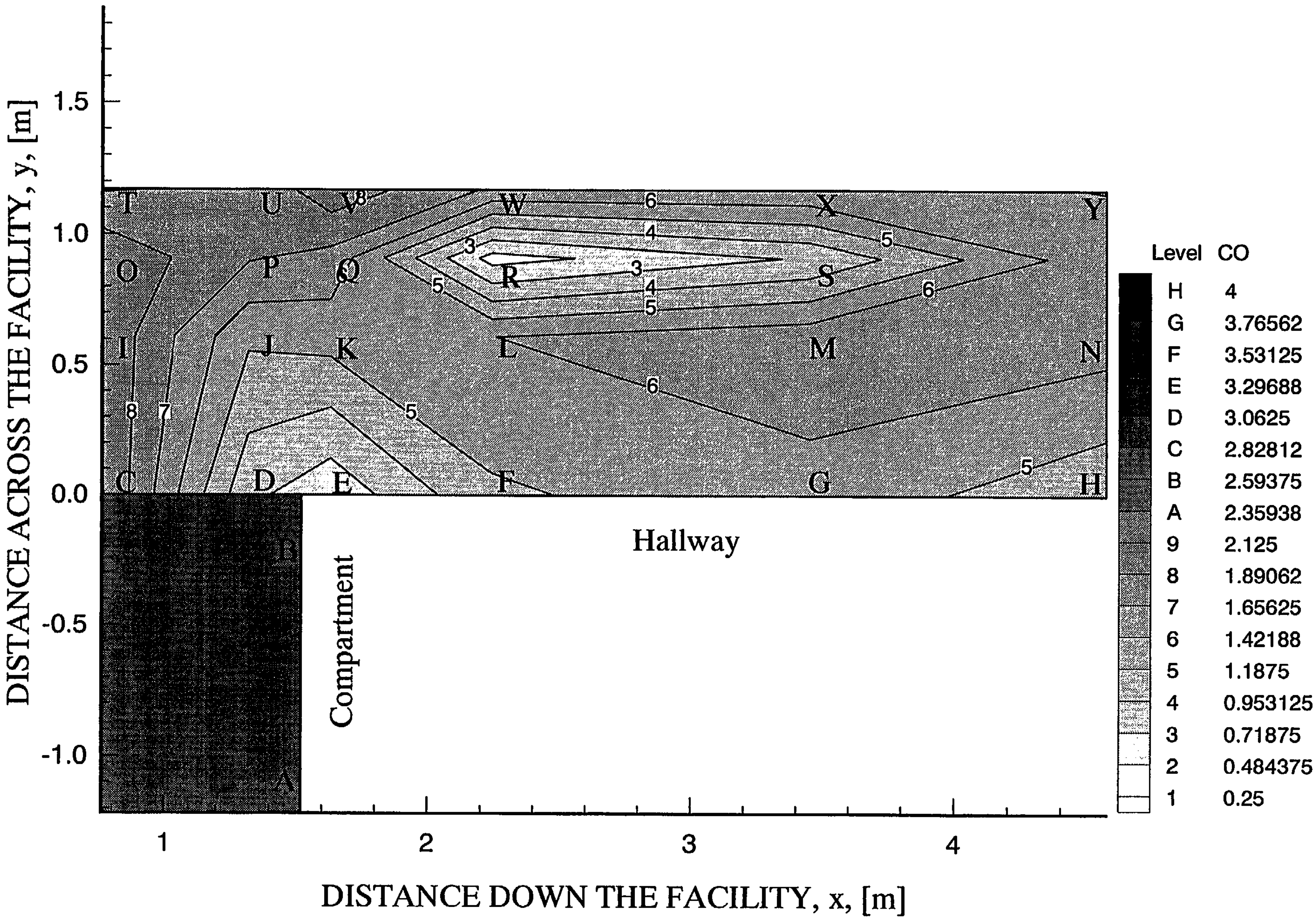


Figure 33. The CO concentration 0.05 m below the ceiling during the 100-110 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

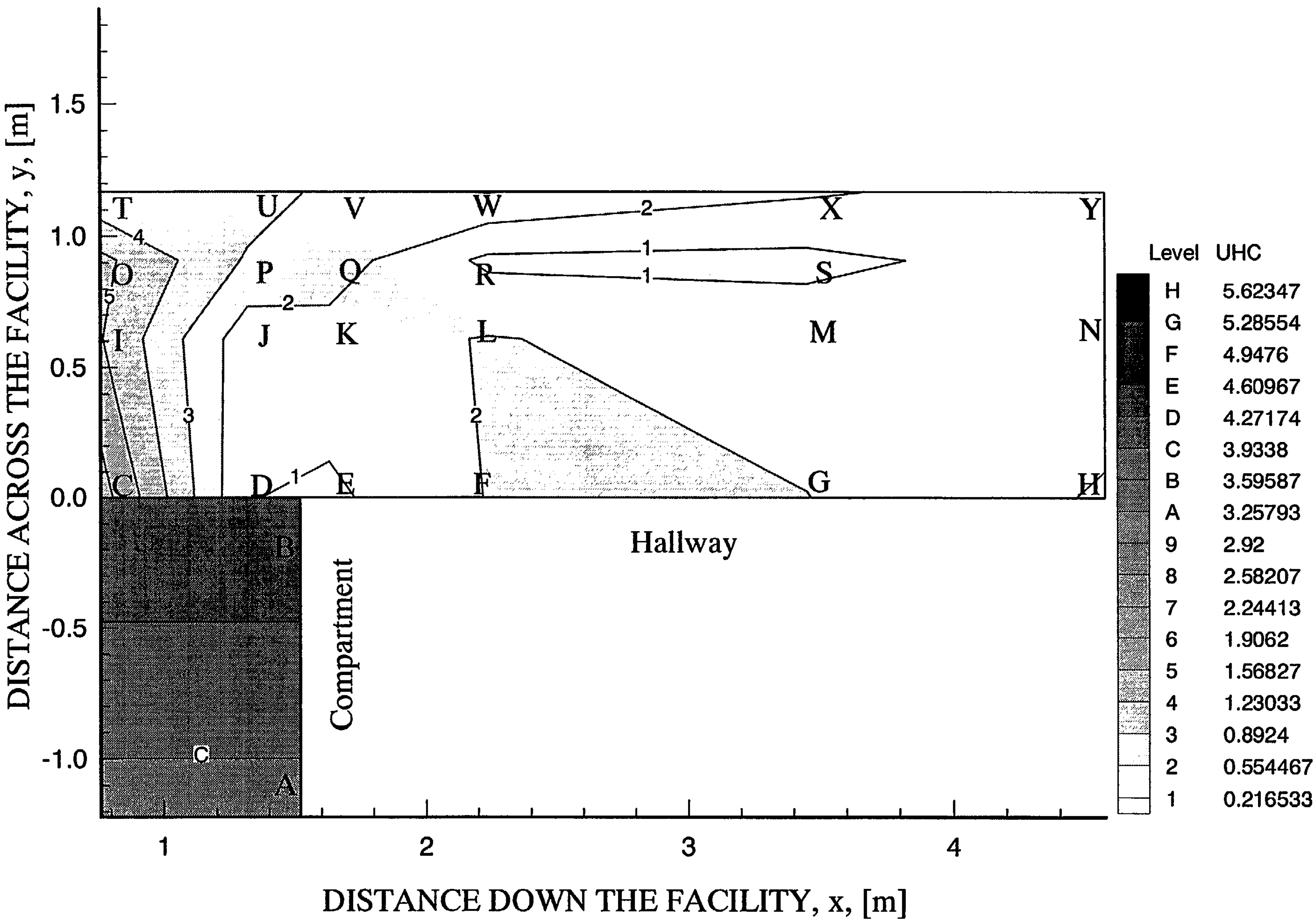


Figure 34. The UHC concentration 0.05 m below the ceiling during the 100-110 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

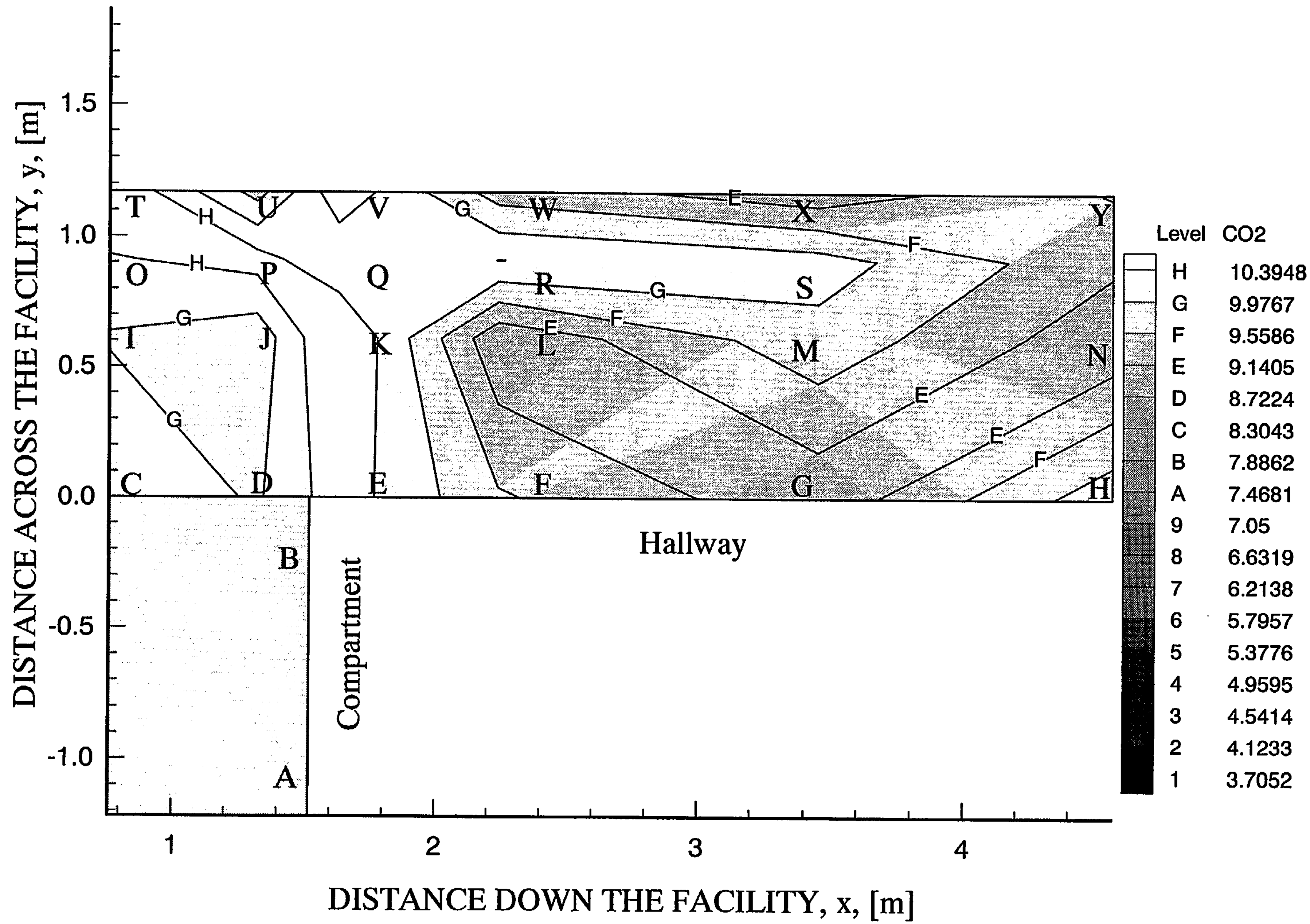


Figure 35. The CO_2 concentration 0.05 m below the ceiling during the 100-110 second interval after with a 0.04 m^2 window and a 0.20 m soffit at the window.

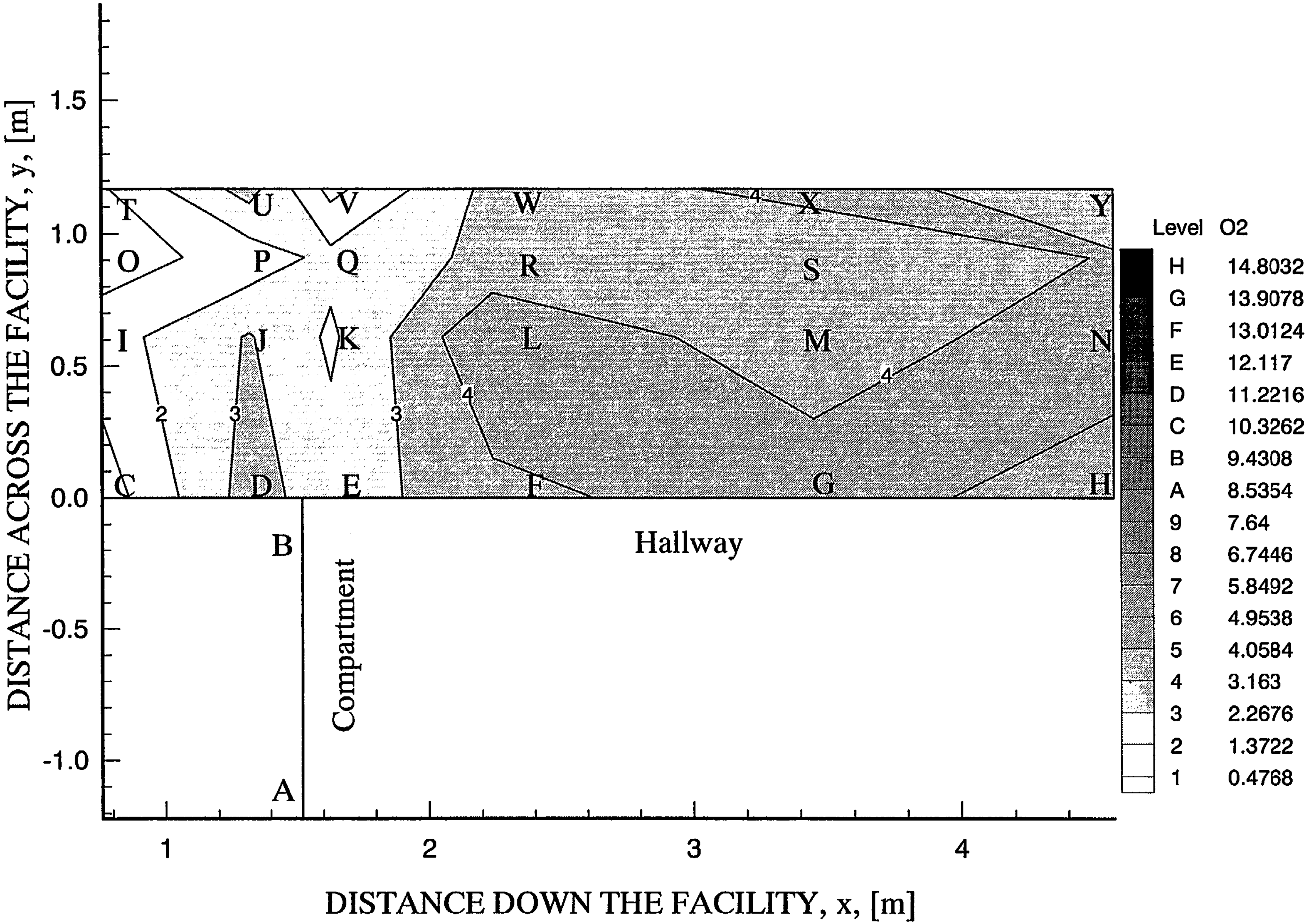


Figure 36. The O_2 concentration 0.05 m below the ceiling during the 100-110 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

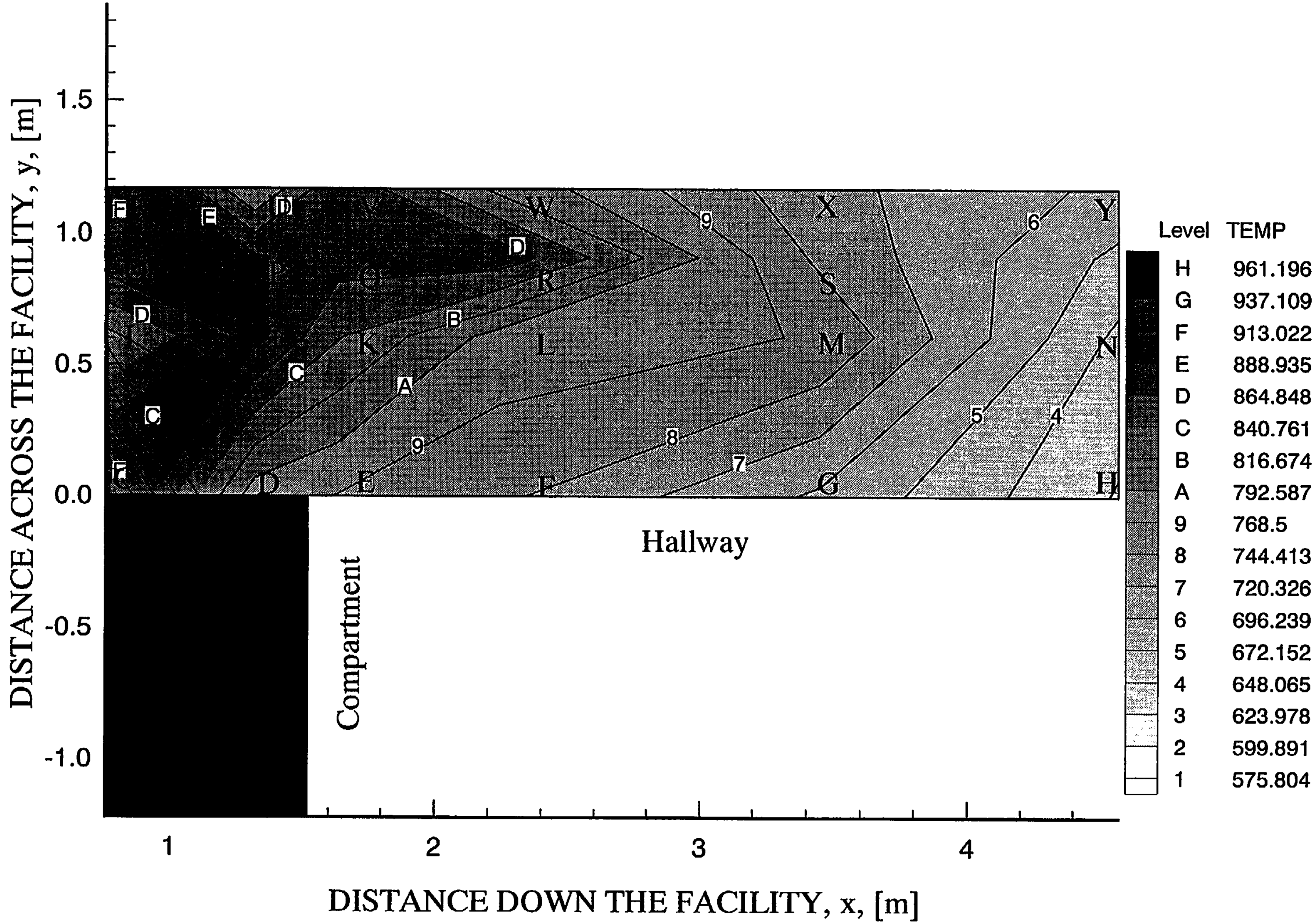
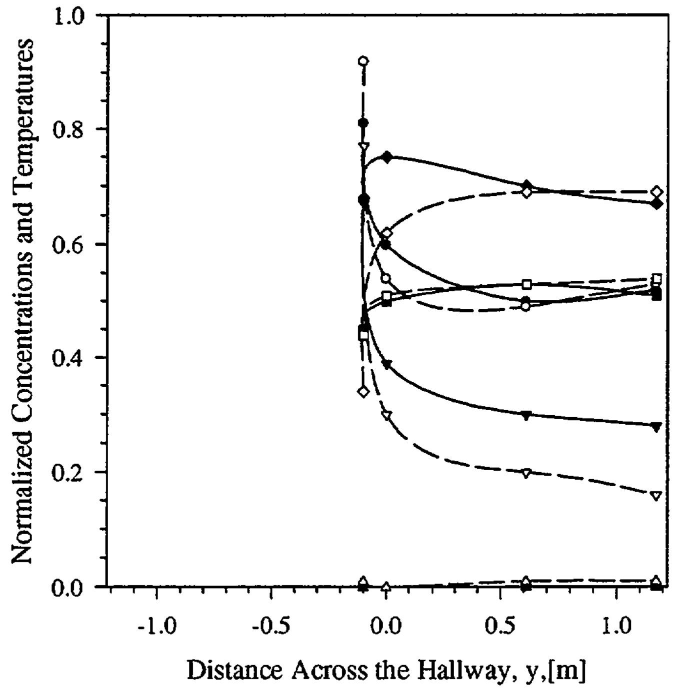
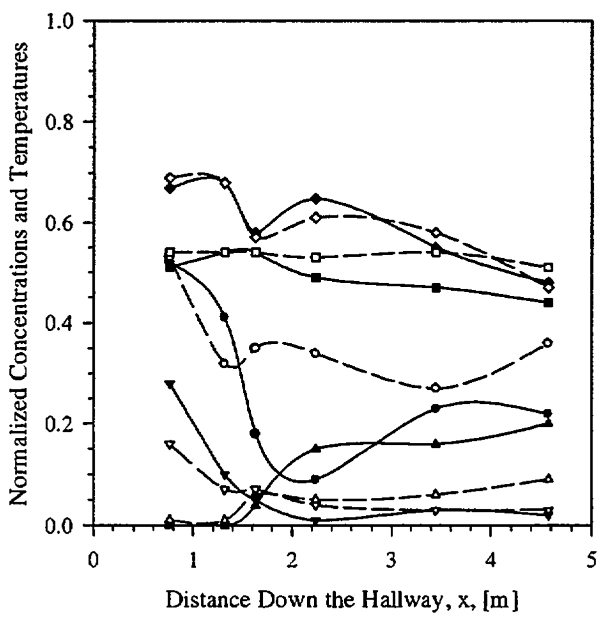


Figure 37. The temperature 0.05 m below the ceiling during 100-110 second interval after flashover with a 0.04 m^2 window and 0.20 m soffit at the window.

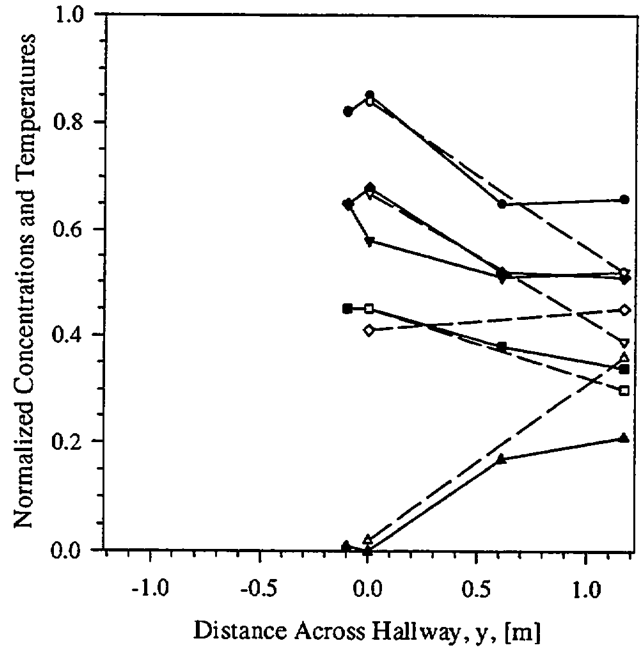


(a)

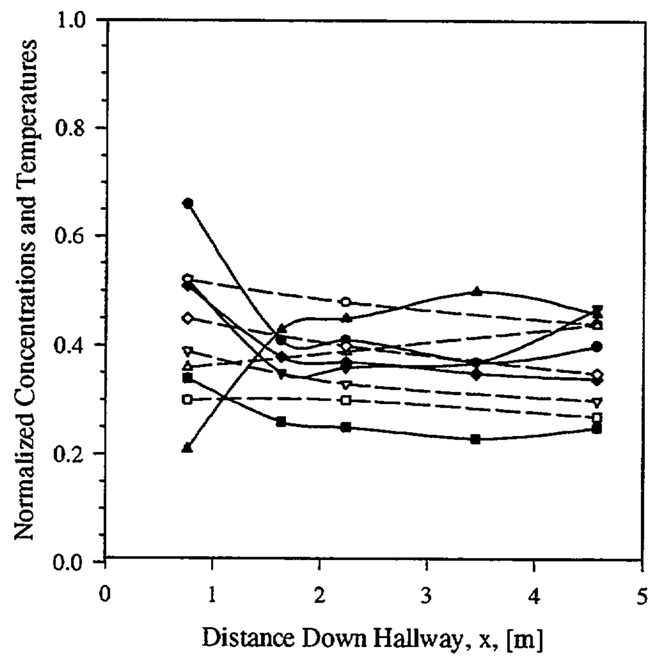


(b)

Figure 38. The variation in the species cocentrations and temperatures for experiments having external burning. The closed symbols are results from experiments with a 0.08 m^2 window and no soffit while the open symbols are results with a 0.04 m^2 window and a 0.20 m soffit. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.



(a)



(b)

Figure 39. The variations in the species concentrations and temperatures in experiments with no external burning. The closed symbols are results from experiments with a 0.04 m^2 window and no soffit while the open symbols are results with a 0.04m^2 window and a 0.20 m soffit. Symbols: ●-CO, ■-CO_2, ▲-O_2, ▼-UHC, ◆-Temperature.

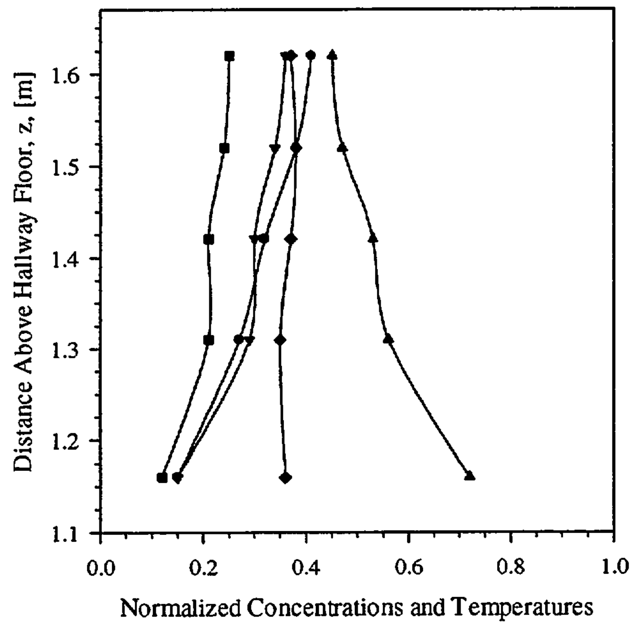


Figure 40. The variation in the species concentrations and temperatures along the height of the hallway with external burning occuring. The results are from experiments with a 0.12 m^2 window and no soffit. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.

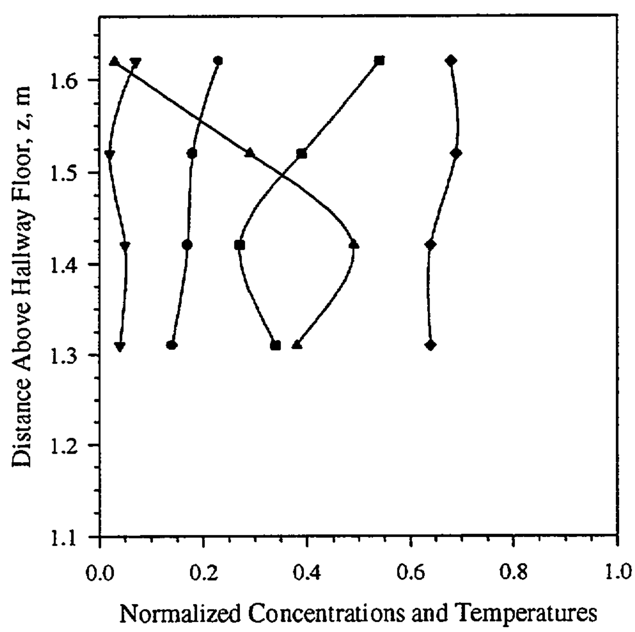
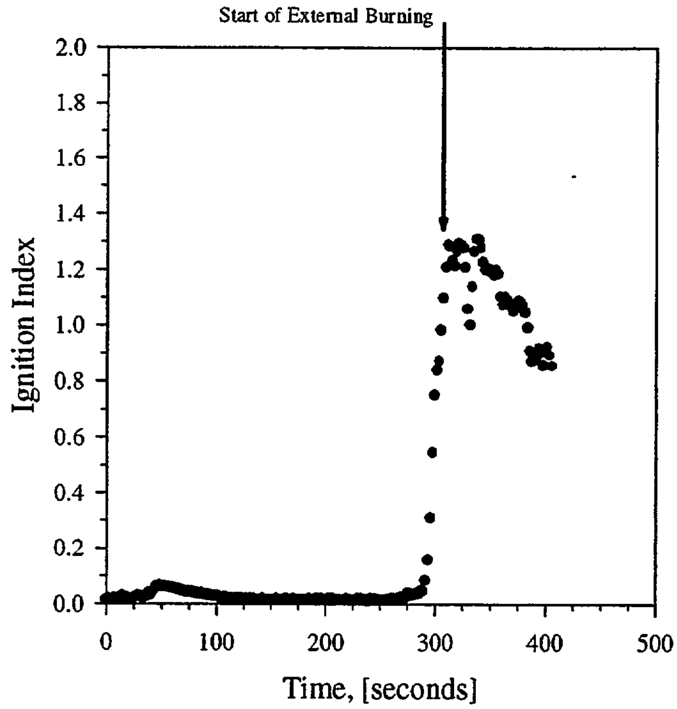
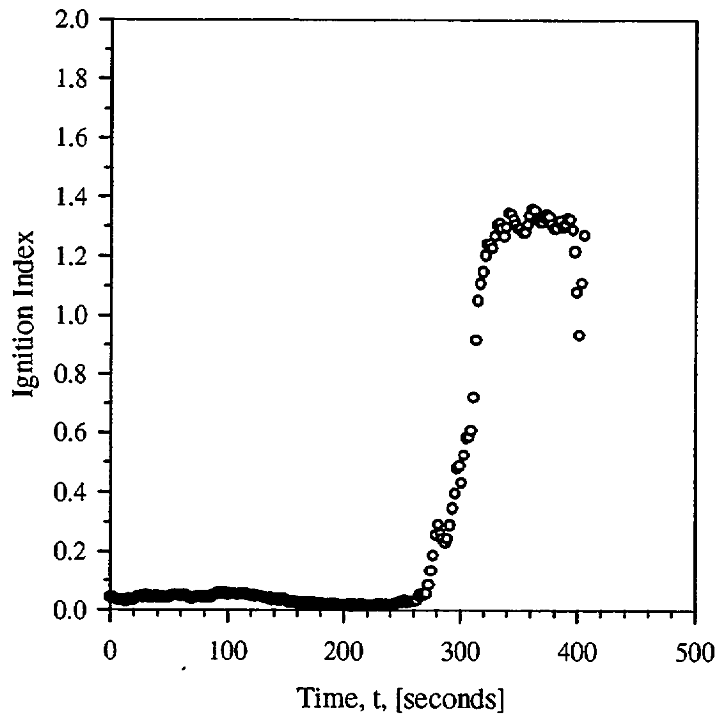


Figure 41. The variation in the species concentrations and temperatures along the height of the hallway with no external burning. The results are from experiments with a 0.04 m^2 window and 0.20 m soffit. Symbols: ●-CO, ■-CO_2 , ▲-O_2, ▼-UHC, ◆-Temperature.



(a)



(b)

Figure 42. Ignition index for experiments with (a) external burning in the hallway and (b) with no external burning in the hallway.

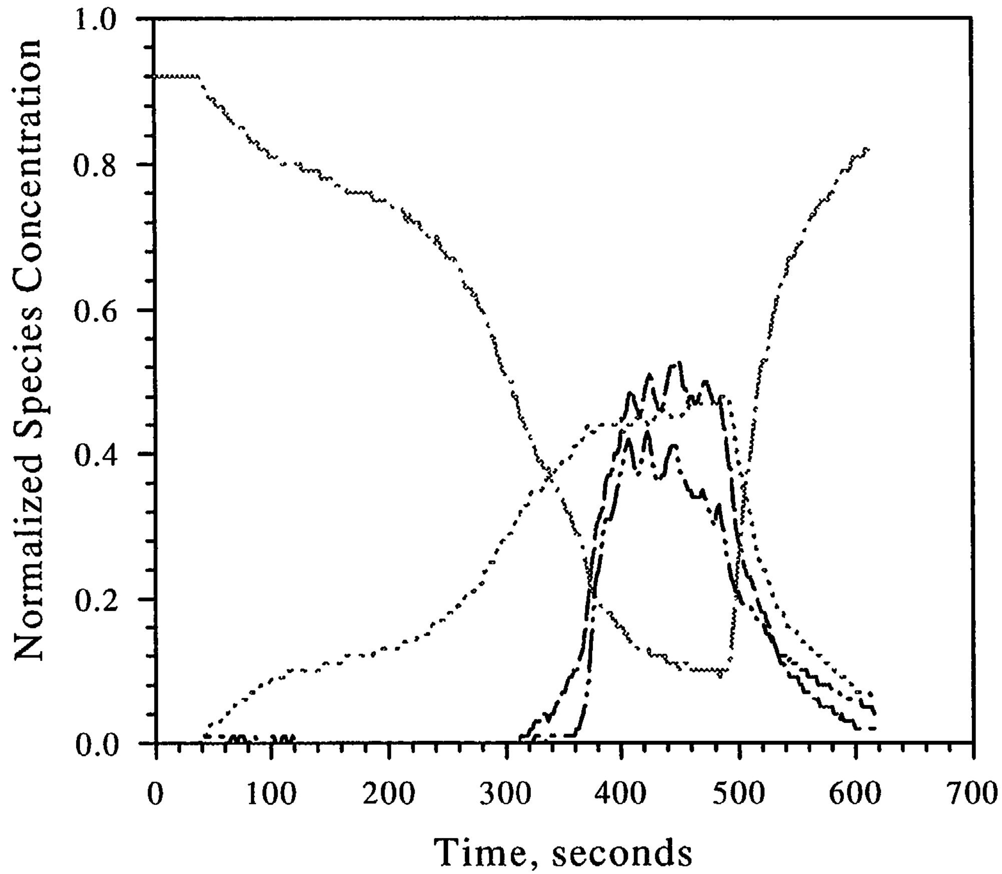


Figure 43. Temporal variation in the species concentrations in an experiment with a 0.08 m^2 window, 0.20 m soffit at the window, and a 1.10 m soffit at the hallway exit. Symbols: --CO,••• CO_2 , -•-O_2, -••-UHC.

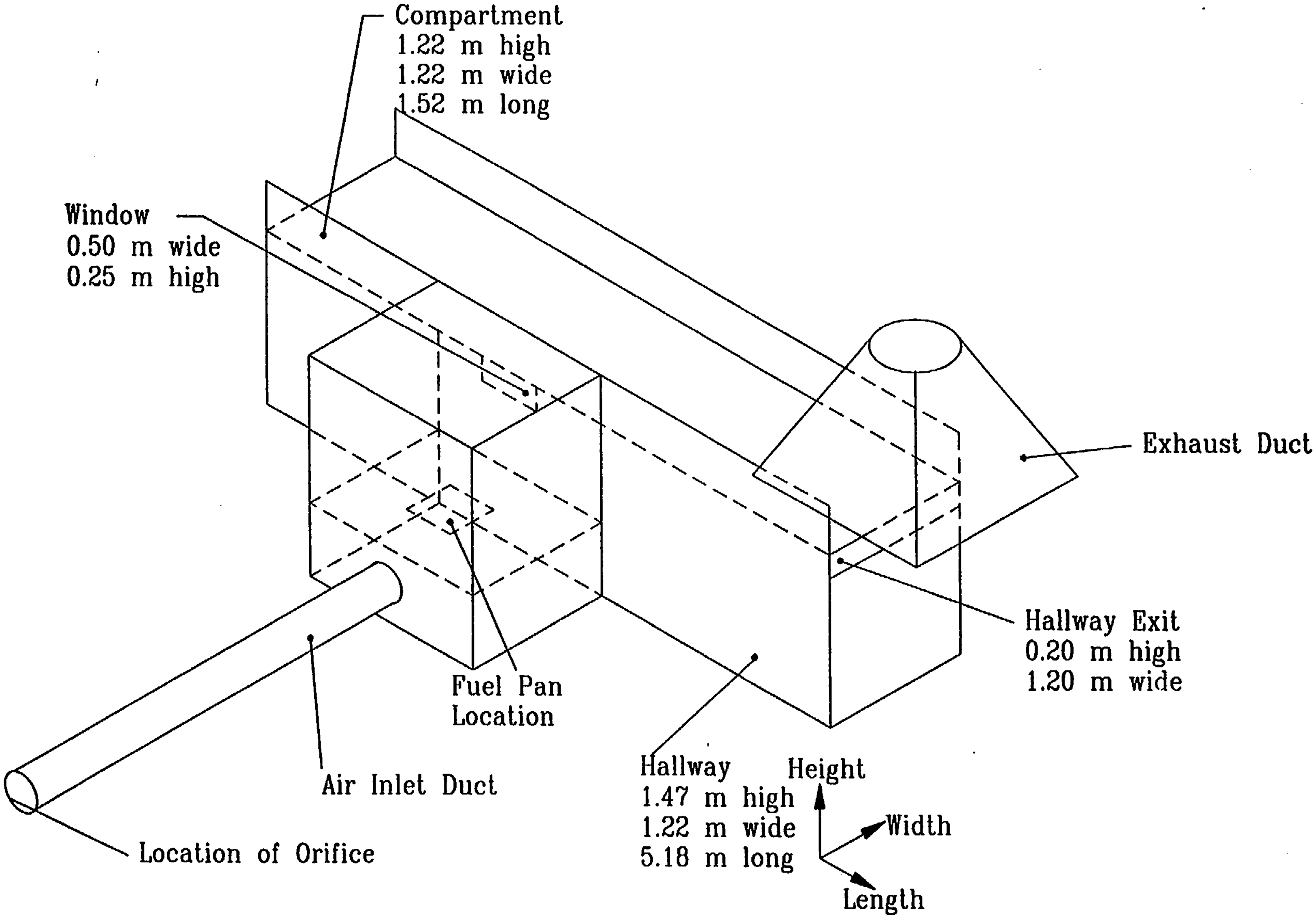


Figure 44. The side-middle hallway-compartment configuration.

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ABSTRACT (A 2000-CHARACTER OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, CITE IT HERE. SPELL OUT ACRONYMS ON FIRST REFERENCE.) (CONTINUE ON SEPARATE PAGE, IF NECESSARY.)

The investigation focuses on the transport of carbon monoxide (CO) away from a burning compartment and the conditions necessary for the existence of fatally high concentrations of CO at remote locations. The study is conducted at the Building Fire Research Laboratory at Virginia Tech. During the past year, the resarch has concentrated on the transport of CO away from a reduced-scale burning compartment located on the side of the end of a hallway. High levels of CO were transported to remote locations by limiting the air entrainment into the plume of compartment fire gases entering the hallway. In experiments with limited plume air entrainment and external burning high levels of CO (2.5-2.8%-wet) were measured exiting the compartment and at locations across the hallway. High levels of CO (1.6-2.4%-wet) were also measured in the gases moving down the side of the hallway opposite the compartment, while low levels of CO (0.4-1.%-wet) were measured in gases along the compartment side of the hallway. External burning resulted in the oxidation of mostly unburned hydrocarbons (UHC), with only 0.5% measured exiting the hallway. The non-uniform transport of combustion gases down the hallway explains the locations of fatalities in previously reported fires.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

air entrainment; compartment fires; combustion gases; carbon monoxide; corridor; fire research; full scale fire tests; hydrocarbons; pool fires; toxic gases

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